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An Integrated Approach to Parametric Associative Design for Powertrain Components on the Automotive Industry

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AN INTEGRATED APPROACH TO PARAMETRIC ASSOCIATIVE DESIGN FOR POWERTRAIN COMPONENTS IN THE AUTOMOTIVE INDUSTRY

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SALEHI V., MCMAHON C., 2009;
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SALEHI V., MCMAHON C., 2011;
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ABSTRACT

The automotive engineering process is characterized by a long and complex design process which starts with the first sketches in the preliminary design phase and proceeds to the final detailed CAD and physical models. In this process, every design phase includes different process steps and tasks which are closely interconnected with each other. Therefore the different design stages demand capable Computer Aided Design (CAD) systems which are able to handle the different kinds of design information created and manipulated in the process. Currently in automotive practice, parametric and associative (PA) CAD systems are widely applied in the product development process. Such systems allow design knowledge to be embedded in CAD models by means of rules and formulae. In addition, CAD parts and assemblies can be generated faster and easier by modification of design parameters and therefore there is a possibility to create different CAD model variants which are based on the same CAD model.

The four key element of the following work are (a) to identify the problems during the design process with parametric and associative (PA) methods during a three year of study and also the analysis of the literature survey. Furthermore (b) in this study the author will develop and implement a newly developed PA design approach (PARAMASS) in a "real" industrial context. Beside this the following work will (c) discuss the issues which are important during the implementation of the developed PA approach in an industrial surrounding. The last key element (d) is to develop an evaluation approach for the PARAMASS approach during the application in an industrial context. In this case the author will be able to do action research in the industry and get first hand information during the accomplishment of these key elements.

This thesis presents the results of a research programme carried out using the design research methodology of Blessing and Chakrabarti, aimed at understanding the difficulties and challenges faced by designers in using PA CAD systems and then developing and evaluating an integrated approach to the creation of PA CAD models in an automotive power train design context. Firstly, this thesis presents a review of the state of the art in PA design methods and approaches and also reviews previous research on the development of methodologies for the construction of PA CAD models. It then presents

the results of a descriptive study of the use of PA CAD tools and methods in vehicle power train design in an automotive original equipment manufacturer and in companies in its supply chain using questionnaires, interviews, tests and other field studies with a number of practising engineers. This study identified a number of issues faced by designers in the use of PA CAD tools and allowed the requirements for improved methods for the use of PA CAD tools to be formulated and indicators identified for their evaluation. Based on the results of the descriptive study a new integrated parametric associative (PA) approach for the design process of power train components was created in a prescriptive study stage. The approach, called PARAMASS, allows designers to construct and modify models in a methodical way based on three main phases: a specification phase to prepare the relevant parameters and associative relationships, a structuring phase that allows part and assembly structures to be created and a modification phase in which the created parametric and associative information can be modified and changed. The method makes extensive use of predefined structures matrix approaches adapted from the Design Structure Matrix.

The prescriptive study phase of the research was followed by a second descriptive study to evaluate and investigate in both a qualitative and quantitative way the changes achieved by the PARAMASS approach. The qualitative evaluation was based on the Goal Question Metric approach and showed that there are advantages related to the reusability aspects like learning, application and acceptance of the developed integrated approach. The quantitative evaluation was based on the Use Case approach and demonstrated good advantages in applying the developed approach, but dependent on the complexity of the created parts and assemblies.

1 Introduction

This thesis reports research into methods that may be used by designers in the process of mechanical design using parametric [1] associative [2] (PA) computer-aided design (CAD) tools. It was carried out through a programme of empirical study in the power train department of a large European automotive company. The research first sought to understand through literature review and study in industry of design practice the designers' experience in the use of PA CAD tools and on the basis of the understanding so achieved proposed an improved systematic approach to PA CAD. This new method was then evaluated through a further study, again carried out in an industrial context, of its application.

The research is important because of the need for capable CAD tools, such as PA CAD systems, in order to create efficient virtual product development (VPD) processes, especially in the automotive industry, which faces huge international competition from the requirements of the global market. This market leads to demands for the highest possible product quality, quick response to market requirements and reduction of costs. In addition to these, companies need new, innovative products to set themselves apart from international competitors. In order to fulfil these requirements and compete globally, automotive manufacturers try to create new and efficient processes based on VPD systems. VPD systems based on PA CAD approaches offer the possibility to connect design knowledge with "intelligent" design solutions, and thus to achieve a faster and more

[1] Parametric system: According to Shah and Mäntylä [SHAH and MÄNTYLÄ, 1995] a parametric CAD-model is labelled by having certain attributes that makes modifications possible without deleting and recreating any of metrical components. For that reason variations are accomplished by modification the values of the parameters. Therefore, to accomplish modifications it is not necessary to delete and recreate the geometry new. Parametric systems solve constraints by applying sequential assignment to model variables, where each assigned value is computed as a function of the previously assigned values. Unlike procedural systems, the order of the assignment is flexible, determined by a constraint propagation algorithm". Further definition of the term parametric will be given in Chapter 3

[2] Associativity: Related to design process, associativity is the fix relationship and connection between geometrical entities and objects. These associative relationships include also the connection of 3D models and down stream process related elements. The parametrization of a 3D model (feature) implies the parametrization of derived information items of this 3D model (feature) that are a result of other applications (draft projections with dimensions or the numerical control programme for the previous examples). By these means, any modification in a 3D model (feature) is automatically propagated to down-stream applications and connected geometries [AIT, 1995]. Further definition of the term associative design will be given in Chapter 3.

responsive produce development process, but the conversion of design intent and information from CAD systems to “intelligent” modelling is not easy. The reason for this is that for many designers it is very difficult to find suitable methods of connecting their knowledge or design intent with such PA CAD systems. According to VDI 2209 [VDI 2209, 2006] during the design process with a parametric system there is a certain “thinking process” necessary or designers need preparative works which include the design, manufacturing, calculation, process and organisational aspects [VDI 2209, 2006]. Therefore a new method is necessary which helps designers to handle this preliminary preparation and consideration phase during the work with PA systems. As a result this step should help to create clear structured CAD models and assemblies. Another new challenge which designers are faced is the question, “How can this kind of CAD system be used best in complex virtual product (vehicle) development”. As a result, design engineers in the automotive industry need an applied method which gives them a certain direction for working with PA design systems. The present work aims to address these challenges by making a contribution to methodological virtual product development especially in virtual vehicle development using PA design.

1.1 Research questions and problem description

The development of modern CAD systems and the change from 2D design to parametric 3D modelling was one of the greatest challenges for many designers. Today designers are confronted with modern CAD systems which allow them to connect their design knowledge and intent with the created CAD parts and assemblies. However, in real industrial contexts the knowledge implementation and adoption of modern parametric CAD systems is not uncomplicated. The reason is that during the knowledge implementation important aspects like product, process and organisation of the company are not fully considered. Furthermore most of the CAD system vendors offer a lot of different functions which are integrated inside CAD systems, such as associative design which allows designers to create associative connections between their geometrical entities and components.

Shah [SHAH, 1993] noted that the task to design a complex parametric CAD model can be very time consuming. According to Vajna [VAJNA, 1998] working with parametric systems requires accurate planning and organisation of the modelling process. This includes not only the embodiment of design with certain CAD systems but also the organisational and process related aspects. Furthermore, because of the complexity of parametric systems, designers should be able to plan a “modelling strategy” for their parts and assemblies. In the case of a PA design process this aspect is one of the most important. The reason that a designer has to clarify how design parameters, associative relationships and design information inputs and outputs can be identified determined and structured. Moreover, it is important to research methods which help to solve the challenge of how to handle the complex associative relationships between the geometrical entities and parameters especially during virtual power train development. These associative relationships can be, for instance, the associativity between the geometrical entities of one 3D CAD element to another 3D CAD model or between a 3D CAD model and a 2D CAD drawing, FEM mesh (Finite Element) or NC-machining (Numeric Control) paths. Modifications on an associative parameter and geometry will be reflected through all applications. For that reason the execution of geometrical or parameter modification has to be managed in a diligent way, where agreements must be defined and the moment at which the geometrical and parameter modification has to be arranged. The associativity between one 3D CAD model to another 3D CAD model and 2D CAD drawing is usually the responsibility of the designers and in this case it is necessary to consider how the identified geometrical interfaces will be communicated and shared between these. Because of the associativity, geometrical and parameter changes can also be reflected in other CAD applications, like Finite Element (FE) analysis.

The next aspect which should also be researched in PA design is the structural organisation of PA parts and assemblies. According to Vajna [VAJNA, 1998] a structure of a virtual product describes the full product at all its different levels. These levels can be divided into product assembly, subassembly and different parts which are stored in certain levels of the assembly. Furthermore, it is also very important how the relationships between the parameters and the associative relationships in the different level of the product are and which methods and preparations are necessary to structure the PA design information. In the early stages of product development, the product assembly and components are defined at a conceptual level and, later in the product development process the structure becomes more detailed [VAJNA, 1998]. It is very important to develop an approach which considers the relevant design information inputs and outputs which are necessary in virtual power train development. Another important aspect which also has also to be considered is process related, i.e. means the availability of certain parameters or geometrical information for downstream processes like Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM) information.

PA design also requires exact time coordination among those involved in the design process. In this case the problems of how to connect the methodology to the process of PA design in virtual power train development have to be considered; this last aspect contains the organisational view of PA design. This includes activities which are important for creating associative relationships and defining geometrical interfaces between all the participants in the design process. Therefore it is critical that the developed method and approach is able to cluster all the required PA design activities.

The results of the aforementioned aspects can be formulated by the following research question. This question has been elaborated as a result of the literature survey (results in chapter number four) and the descriptive study I of the following work (results in chapter five):

"What integrated method (approach) is necessary to allow the better application of PA CAD systems in power train development and how is possible to evaluate the impacts?"

In order to answer this main question a number of objectives were addressed in the research and will be reported in this thesis, as follows:

1. To identify, as a base-line for the study, the state-of-the-art in PA CAD system development and practice, especially as concerns methodological approaches to their application.
2. To understand the difficulties and challenges, especially methodological issues, for CAD designers during the design process with PA CAD systems, and through this understanding to identify the important criteria and factors which should be considered during the design process with PA CAD systems.
3. Based on the understanding achieved in 1 and 2 to propose new approaches for the systematic application of PA CAD systems and to incorporate the most effective of these into a new integrated methodological approach.
4. To implement the developed PA approach in an industrial context.
5. To create and apply an evaluation framework to evaluate the effectiveness of the new approach.

To address these objectives a four-phase research programme was undertaken using the Design Research Methodology of Blessing and Chakrabarti (which will be explained in more detail in Chapter 2) [BLESSING/CHAKRABARTI, 2002]. These four phases comprised a Criteria phase, to identify success criteria for the work, a first Descriptive Study phase, which used literature study and empirical research to address objectives 1 and 2, a Prescriptive Study phase which addressed objectives 3 and further empirical research to address objective 4 in a second Descriptive Study phase. All of the empirical work was carried out in an industrial context, with practising designers and CAD trainers in an automotive design office. The research makes contributions to engineering design knowledge in the deep understanding that has been achieved of the issues in the application of PA CAD in practice and in a new systematic approach to PA CAD, called PARAMASS, that offers clearly demonstrated improvement in the time to create and modify PA CAD models and in the structure of the models.

1.2 Research aspects and goals of this thesis

The goal of the work presented in this thesis was to research design methods using PA design systems. This includes investigation and analysis to understand the possible aspects which are important during the design process when using PA systems. Therefore this work will focus on the following aspects:

- To research and identify the **difficulties and challenges**, especially methodological issues, for CAD designers during the design process with PA CAD systems and to identify the important **criteria and factors** which should be considered during the design process with PA CAD systems. Furthermore it is important to research the **structure** of PA CAD parts, assemblies especially in virtual power train development and to research the methods for working with PA design systems. Therefore the following work will research the application of standard CAD parts and assembly models for virtual power train development. This standardization should also help to develop a continuous and modelling process with PA systems.
- To **develop an integrated approach** for the use of PA CAD systems.
- To **implement** the developed approach in an industrial context and surrounding.
- To **develop an evaluation framework** for the qualitative and quantitative assessment of the developed PA approach.

1.3 Boundaries of the following thesis

This section describes the boundaries of the following work. During the work with a PA design system there are different aspects related to the virtual power train design process. These are data release management, data exchange management, data change management, simultaneous and concurrent engineering, CAM, CAE and supplier integration. Furthermore there are dependencies between the above mentioned aspects. Because of the complexity and time constraints, the research chose not to consider all the above mentioned aspects fully. But first of all it is important to clarify the general boundaries and constraints of the following work. According to the E-G-I-P-T [3] model [KIM, 2007] there are five perspectives which can be considered. These perspectives are Environment, Groups, Individuals, Practices and Tools. The following work will research the work with PA systems in the automotive industry especially in virtual power train development and therefore the results are more **practice** oriented than theoretical. That means one of the targets of the following work is to analyse the situation and methods which are currently used in the virtual power train development. Furthermore the ways of working, techniques, processes, methods and tasks which are related to the PA design process will be considered. In addition the above mentioned aspects help to have a better understanding of current methods and practices with PA design and related engineering activities. Perspectives which will not be considered in this thesis are tools and environment. The reason is that in this case the CAD system (PA tools) is well defined. The CAD system which is used in the following thesis is CATIA V5 from Dassault Systems in France, but it was an important consideration that the new developed method will be a universal approach and completely independent of a certain CAD system.

The next perspective of the E-G-I-P-T model [KIM, 2007] is the ‘group’ which considers in this case the PA design knowledge sharing in design work and expertise, as well as the nature of the associative data sharing aspects. The perspective ‘individuals’ (designers) is also important because it is very useful to have an understanding what the difficulties are for designers during the work with PA design process. The PA design process requires a new and close way of working which means that this kind of process is more “cross

[3] EGIPT was proposed in the context of knowledge management but it is suggested that it can apply more generally in design support systems

networked" than concurrent or simultaneous. Figure 1 shows the different perspectives related to the following thesis and PA design.

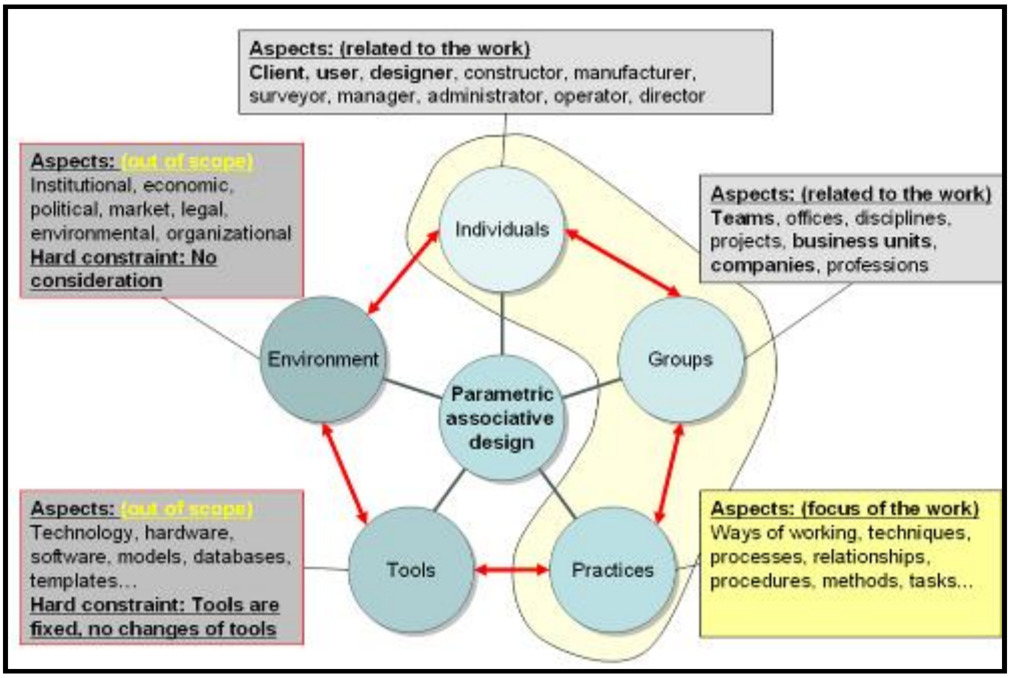


Figure 1: Perspectives of the E-G-I-P-T model [adapted from KIM, 2007]

Figure 2 shows the intersection between different fields which are relevant for the following work. The thesis will only consider virtual power train development in the automotive industry.

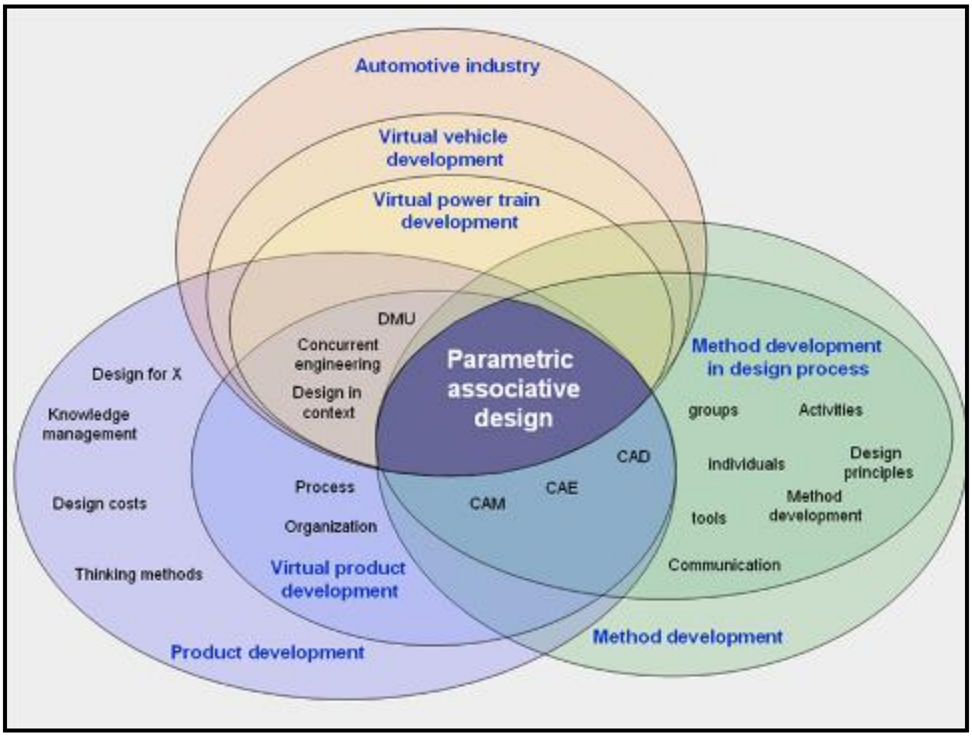


Figure 2: Identification of the boundaries and intersection of the following thesis

The aforementioned boundaries of the following work are summarised below:

- No consideration of product data management system (PDM) aspects. This means that the following work will not investigate on how to handle the PA information in data bases (data storage methods, data security, data access control etc.).

- No consideration of data exchange aspects. This means that the following thesis will not consider how the PA data has to be exchanged between different parties (for instance between OEMs and suppliers).

- No consideration of the change management process. This means that the following work will not investigate the data change management process. It will only suggest a method how to deal with different kinds of changes during the design process with PA design systems (for instance geometrical, non geometrical and administrative changes).

- No consideration of geometrical release management. This means that the following work will not describe a new process or method of how to deal with release management in design process.

1.4 Structure of the thesis

The reporting of the outcomes of the research carried out to address the research question and objectives has led to a thesis with the following structure:

Chapter 1 presents the scientific background of the thesis and defines the research question and objectives of the research. In addition the boundaries of the thesis are defined and explained.

Chapter 2 will present some selected design research approaches and methodologies relevant for the research and will also present and explain the selected design research methodology. In addition there are also descriptions of different methods which are used in the analysis phase of the selected design research approach (i.e. questionnaires, experiments, tests, observation and interviews).

Chapter 3 describes the general application aspects of CAD approaches in the virtual product development process and explains parametric design techniques and the specific characteristic of the different approaches. In addition this chapter will give a definition of the terms PA CAD design by means of presented CAD examples.

Chapter 4 reports the current state of development of methods in product development processes. Design methods related to the research can be divided into general design methods and those relating especially to the application of PA CAD techniques. Furthermore, there are definitions of the term “method” and “methodology” from different scientific viewpoints. In addition this chapter includes an evaluation of different reviewed papers and research theses which are relate to PA design from different aspects.

Chapter 5 presents the results of Descriptive Study I which was accomplished to demonstrate the weaknesses and challenges during the design process with PA CAD systems in the automotive industry especially in the power train design process. The target of this chapter is to elaborate and identify the key criteria and indicators which should be considered during the development and evaluation of PA CAD design approaches. For the identification of the important indicators and factors, CAD designers, trainers and experts have been questioned and interviewed and models produced using conventional processes analysed. As a result a list of requirements which contains important aspects related to the developed PA approach was generated and is presented in this chapter.

Chapter 6 present the newly developed integrated PARAMASS approach for the design process using PA CAD systems which is based on the criteria and indicators from Descriptive Study I. That means in this chapter the results of a Prescriptive Study will be presented. Beside the above mentioned aspects this chapter will also elaborate criteria which are important during the planning, introduction and implementation of the developed integrated approach in an industrial context.

Chapter 7 presents the implementation of the developed PA approach, identifying the important aspects like planning and preparation works during the implementation of the approach. It also presents recommendations which should be considered during the planning and introduction of PA design methods.

Chapter 8 presents the results of the Descriptive Study II[4] which contains the evaluation of the developed PA approach. An evaluation framework will be presented to assess the identified criteria and indicators of the approach. It will also present qualitative and quantitative approaches for evaluation of PA approaches in an industrial context.

Chapter 9 concludes the thesis and presents the key results and achievements of the research. Furthermore this chapter will give an overview about further research steps and possible domains which should be considered in the future. The structure of the following thesis is shown in Figure 3.

[4] The terms Descriptive Study I, Prescriptive Study and Descriptive Study II define the steps of the selected design research methodology (DRM) according to Blessing and Chakrabati. The different steps of the approach according to Blessing/Chakrabati will be explained in Chapter 2.

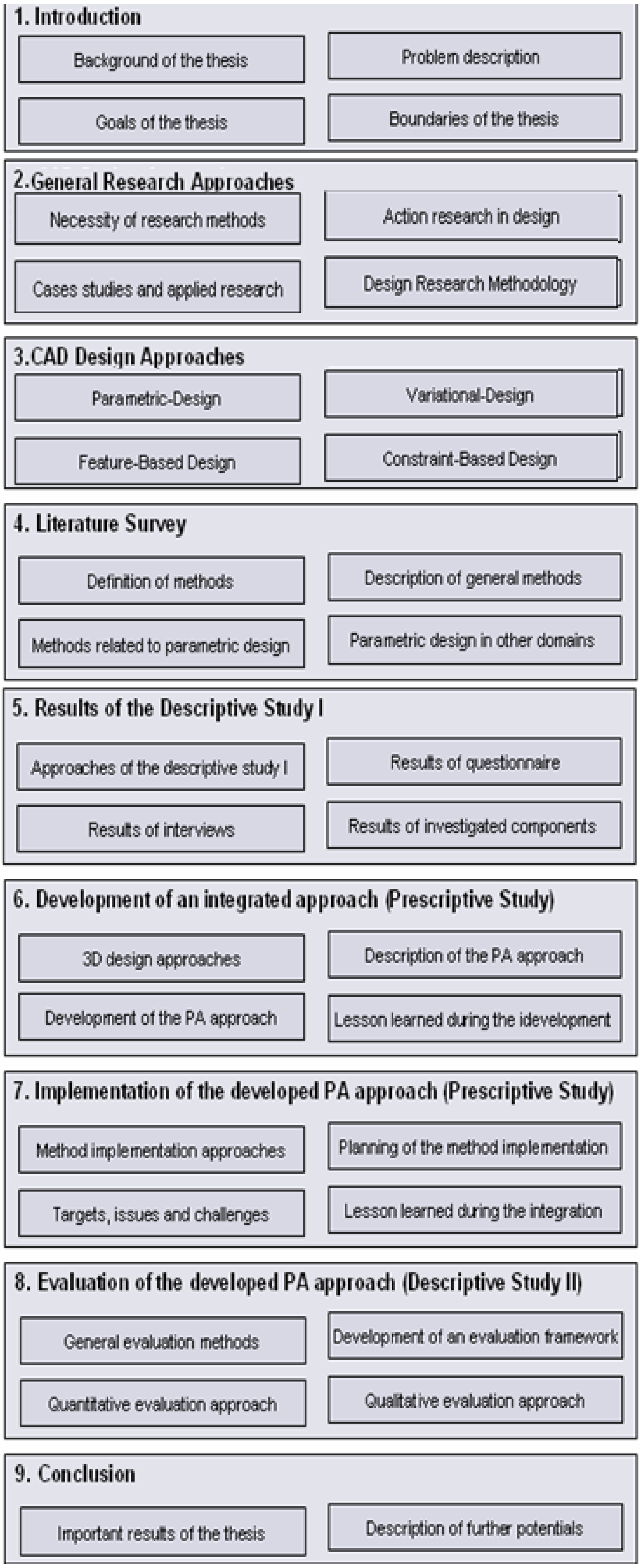


Figure 3: Structure of the thesis

2 Research approaches and methodologies

One of the most important points of every scientific work is the explanation of the research methodology which gives an overview of the way of the research has been undertaken. This aspect includes the question of how the research intention was addressed and what steps were necessary to work in a systematic way. This section of the work describes general characteristics of scientific work and methodologies [OTTOSSON/BJÖRKE, 2006], [BAYA, 1996]. After the description of different methodologies the author will identify the approach which was used to accomplish the research. In the field of research Vajna suggests that scientific work can be divided into two broad fields [VAJNA, 1998]. The first field comprises basic research which looks for fundamental principles. The second area is the applied sciences, which concerns the adaptation of new knowledge to real problems. Vajna describes scientific investigations as an intersection of complex system problems which can be solved by means of practical and theoretical research. The present study can be considered as applied science work. That means that the results of the research will be applied in a real industrial environment and therefore the results are more applied than theoretical. In design research approaches Vajna also distinguishes between quantitative and qualitative research [VAJNA, 2006]. The characteristic of the quantitative research approach is that it starts with a hypothesis on some theory or a previous statement and it is often systematic but un-contextual [SCHEFF/STARRIN, 1996]. The qualitative research approach, which is contextual, may happen in an "unplanned" way in reality [SCHEFF/STARRIN, 1996]. Furthermore, the qualitative research approach does not accept the traditional positivist view of separating reality into subject and objects. According to Ottosson and Björke [OTTOSSON/BJÖRKE, 2006] the qualitative research approach is important as a main research method for empirical studies. In addition a qualitative research approach in general starts with rather open questions. The purpose of the science in general is always a subjective perception and description of reality [ULRICH, 1976]. In addition real science exactly describes subjectively perceived parts of the reality in order to generalise and sketch alternative actions [ULRICH, 1976]. Baya [BAYA, 1996] mentioned that design research methodology should consider three important points: (a) grounding the research in reality (b) understanding the design process and (c) improving design practice. For the accomplishment of these points, Baya used methods like observation and experiments.

Björk [BJÖRK, 2006] described the Insider Action Research (IAR) approach in design process-research, which enables researchers to interact inside the observation teams for the identification of problems during the design process. Related to the following work the researcher had the unique chance to accompany the designers in different departments which worked with PA CAD systems. In this case it was possible to get first hand information from the designers and be part of the team. The next sections of the following work will explain different kinds of research approaches and their characteristics. At the end of this section the research approach which has been selected to accomplish the following work will be explained.

2.1 Learning Cycle of experience, knowledge and learning

Carrying out research tasks in an industrial context clearly implies that the experiences of the researcher involved in that particular organizational setting play an important role. Through the application of a scientific framework the problematic issues can be identified. The problems identified and the proposed solution approaches to these problems can be validated through experimentation in the organizational setting in an action research oriented and case study based approach [CLAESSON/JOHANNESSON, 2006]. A general framework which describes a basic learning cycle is defined by Kolb [KOLB, 1984]. It starts with a concrete experience from a certain problem or situation of the process. Kolb also states that a concrete observation of certain issues that are made on the basis of the knowledge obtained and experience lead to the formation of “new” or improved concepts and generalizations [KOLB, 1984]. These new or improved concept and generalizations lead to ideas for a new approach. The new approach, its concepts, and its generalizations with the corresponding implications must be formulated and then tested in new situations through active experimentation. Through this testing, of course, new experience and knowledge follow that make the start of a new learning cycle [KOLB, 1984] (Figure 4).

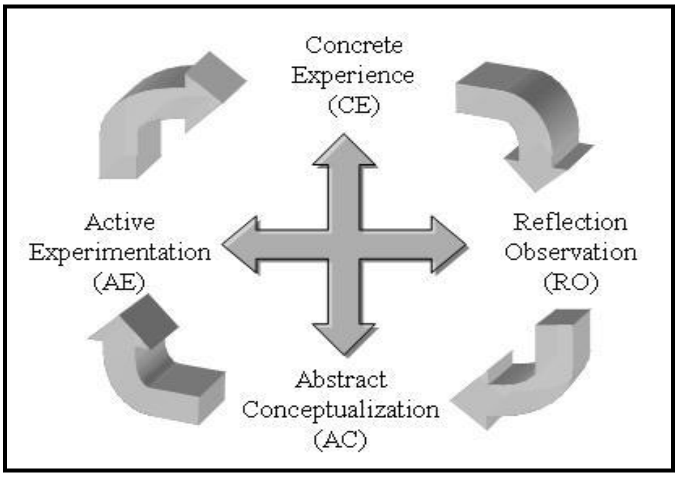


Figure 4: A basic learning cycle according to Kolb [KOLB, 1984]

This framework of a basic cycle for knowledge elicitation can (as mentioned in the text above) be further improved and systematized in order to offer scientific rigor through the application of additional scientific frameworks, approaches, and methods at different phases along the basic learning cycle. According to Claesson [CLAESSON/JOHANNESSON, 2006] in developing an application of this model, Kolb has helped to challenge those models of learning that seek to reduce potential to one dimension such as intelligence. He also recognized that there are strengths and weaknesses, for example: (a) it pays insufficient attention to the process of reflection; (b) the model takes very little account of different cultural experiences/conditions; (c) the idea of stages or steps does not sit well with the reality of thinking; (d) empirical support for the model is weak and (e) the relationship of learning processes to knowledge is problematic. Because of the above mentioned reasons the adoption of the approach according to Kolb for the following work would be very challenging.

2.2 Framework for modelling, analysis, and implementation

The product development process deals with the issue of how to produce the required product diversity for the clients while making efficient utilization of product platforms [CLAESSON/JOHANNESSON, 2006]. The framework according to Duffy and Andreasen [DUFFY/ANDREASEN; 1995] is illustrated in Figure 5 and consists of a phenomenon model as the first step in the analysis of reality and its problems, needs and potential solutions. From the understanding provided by the phenomenon model an information model can be defined. The information model in turn provides the foundation for the conception and development of an implemented computer model. The models generated are furthermore checked and validated against the previous models [DUFFY/ANDREASEN; 1995] (see feedback loop in Figure 5).

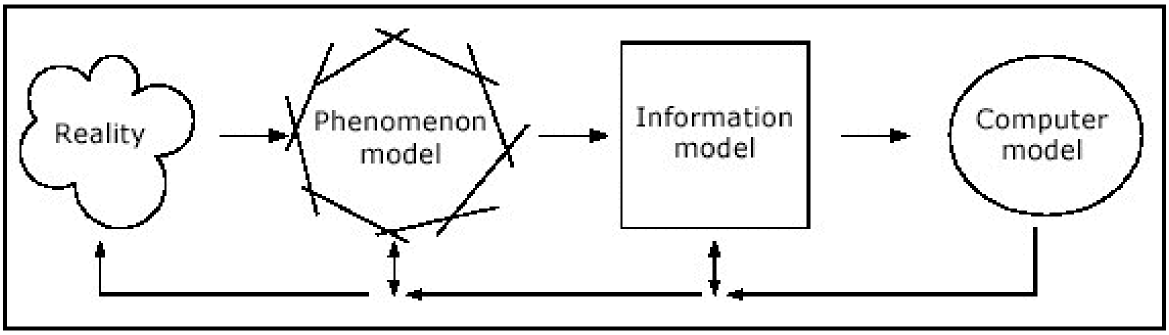


Figure 5: Design research modelling approach [DUFFY; ANDREASEN; 1995]

According to Claesson [CLAESSON/JOHANNESSON, 2006] in order to contribute to the evaluation and progress of design methodology it is intended that models build upon the reality of a design context. These models are then continually evolved to develop methods and tools to support design work. Phenomena models are primarily based upon observations and analysis of the reality of a design context and the current use of the methods and tools employed. Where appropriate, the phenomenon models can be developed in more detail as information models. These information models seek to label all relevant object types and their relations. Computer models are often used to store such product information. At each stage any model can be compared or evaluated against any previous model in order to enhance understanding”. According to Mortensen [MORTENSEN, 1999] the procedure of the approach describes the “whole” research accomplished where “phenomenon models” are slowly formalized by means of information and computer model. The path from right to left is verification and validation, by means of which the models are confronted with and evaluated based on reality, i.e. empirical observations [MORTENSEN, 1999].

The different kinds of computer models can be applied and used for many different purposes. Furthermore models for example can be used to create the same understanding of the different issues and tasks. As demonstrated in Figure 5 the models can be integrated inside computer models that can be implemented in tools used to support product definition and analysis, simulation and other purposes [CLAESSON/JOHANNESSON, 2006]. But related to the following work the above mentioned approach does not explain and elaborate the relevant criteria and indicators for the research aim and purpose. From the design research perspective methods are necessary which are able to reflection the situation before and after the solution process. That means for example how is it possible to identify challenges and difficulties of the current design process and what kind of solution approach is necessary. At the end of the process it should also be possible to demonstrate the changes or possible improvements through the application of a certain solution approach.

2.3 Design Research Methodology (DRM approach)

As explained in the previous sections there are different approaches for the accomplishment of research activities. To focus the research work it is therefore necessary to apply some guiding mechanisms. The framework that has been used to guide the research work presented in this thesis is according to Blessing/Chakrabarti and this approach is described here. Furthermore this section of the work will explain the different steps of the approaches according to Blessing and Chakrabarti. The framework in Figure 6, proposed by Blessing and Chakrabarti [BLESSING/CHAKRABARTI, 2002], defines a research methodology starting with a conceptual framework where criteria that describe the success of the research work and features that influence the success are identified.

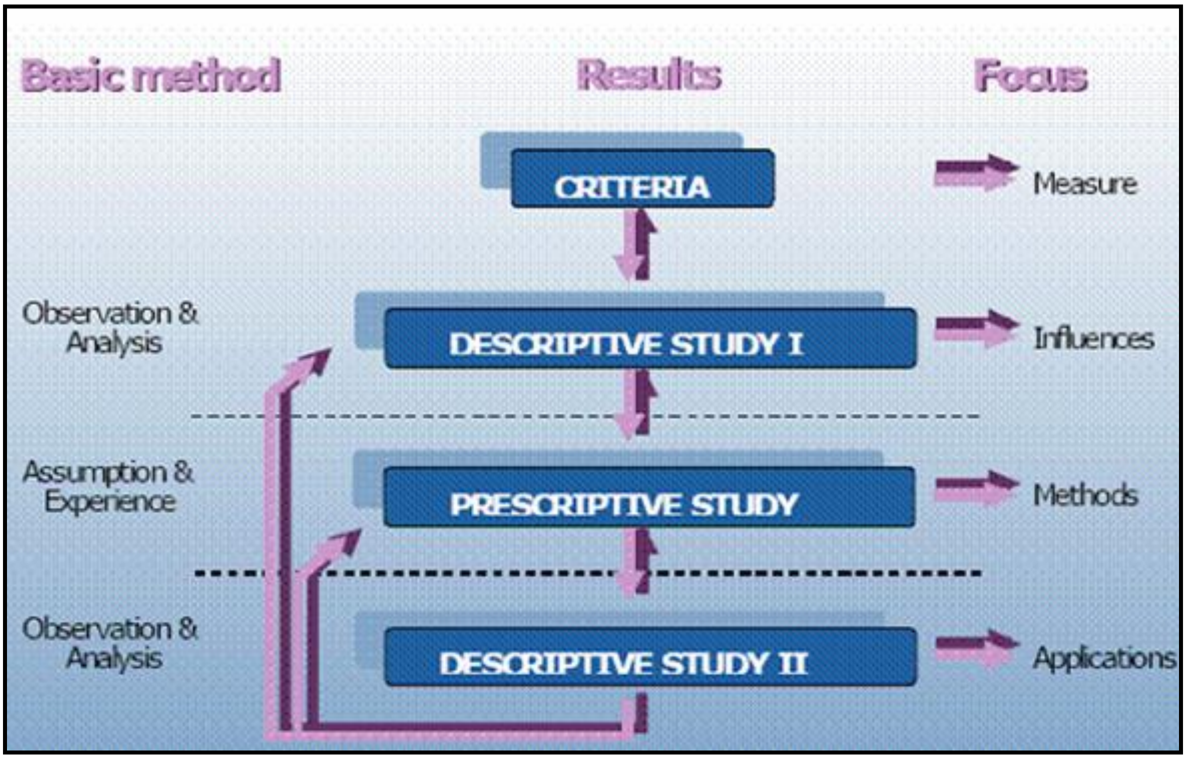


Figure 6: Design research methodology [BLESSING/CHAKRABARTI, 2002]

According to the framework, the first step is to define the criteria to be addressed by the research. These criteria include both a scientific research perspective and an industrial perspective. These criteria could be research goals, objectives, constraints, success criteria and measurable criteria. Industrial criteria could be to reduce lead-time in product development or to improve quality [BLESSING/CHAKRABARTI, 2002]. However, such high level industrial criteria must be further refined into a set of more focused criteria and influencing factors that can actually be addressed within the scope of the research project [BLESSING, 2002]. An understanding of the subject under study is obtained on the basis of observation and analysis (description I). Using experience and assumptions an approach to deal with the problem under study can be defined (prescription) [BLESSING/CHAKRABARTI, 2002]. If the prescription defined is applied to the subject under study in some form of intervention the relevance of the first understanding (description I) and the effects of the applied approach (prescription) can be observed and analysed (description II). Based on this new understanding the first description and the prescribed approaches can be evaluated and validated or improved [BLESSING/CHAKRABARTI, 2002]. In another work, Blessing [BLESSING/CHAKRABARTI, 2002] criticises the fact that there is no uniform method in the field of design research. Many approaches do not consider the following aspects:

- There is no established method of doing design research.
- There are only partial approaches to design research, like making observations and experiments. This partial approach does not consider the whole research process.
- There are limited links between factors which have influenced the design process and the success of implemented improvements.
- There are not sufficient methods which compare the situation before and after the design research.

Many existing design research methods do not consider the above-mentioned aspects. However the design research methodology according to Blessing [BLESSING/CHAKRABARTI, 2002] considers most of the above mentioned aspects. For that reason the present research will use the design research methodology according to Blessing and Chakrabarti. The reason is that this approach is the most suitable one because it allows researchers to generate a research process with consideration of very important aspects like data sources, documentation of research results, definition of measurable criteria and success, definition of a reference model ("as is" process) and the subsequent comparison with the "to be" process. The different stages and the application of the DRM approach according to Blessing/Chakrabarti will be explained in this section.

2.3.1 Definition of criteria

The first step of the Blessing/Chakrabarti DRM (BC DRM) [BLESSING/CHAKRABARTI, 2002] is to define the criteria, the basic goals and purpose of the scientific work. For a scientific research area, such as design, which intends to improve a situation like design tasks or processes, establishing success criteria is very important. In this way it is possible to verify the different criteria that have an influence on the success of the design process. These influences can be positive or negative and the main goal is to reduce the negative factors and support the positive ones. Furthermore in this phase the measurable criteria will be defined. At the end of this phase the defined criteria will be the basis for evaluating the success of new design knowledge. According to Blessing in this phase there is a need to formulate both success and its measurable criteria. The main tasks of these criteria are [BLESSING/CHAKRABARTI, 2002]:

- The identification of the aim that the research work is expected to reach and the focus of the research project.
- To focus Descriptive Study I on finding the factors that contribute to success.
- To enable evaluation of the developed support (Descriptive Study II).

Blessing and Chakrabarti also states that success criteria depend on the overall aim of the design research, i.e. the question of ‘why’ in the design research. In addition, these criteria are usually associated to normal business or market success. They can also be technical or political such as reduced product development time or getting a better company image. But the weak point of much design research works is the bad quality of the various links between the factors used to measure the design research results, which are often not made clear or precisely enough and therefore seem to be regularly created on some assumption rather than on evidence [BLESSING/CHAKRABARTI, 2002]. In some cases it is also difficult to demonstrate in which way the research project has achieved its targets. There is insufficient well-documented data about the achieved results in design research or analysis processes. The reason [BLESSING/CHAKRABARTI, 2002] for that can be the fixed period of a design research project, which does not allow exact measurements and long-term studies of possible improvements and effects. Therefore it is one of the most important points to define and clarify at the beginning of every design research project the measurable criteria which allow translating research intentions such as benefits, measurable factors and criteria.

The definition of measurable criteria is not easy [BLESSING/CHAKRABARTI, 2002]. It is true that an empirical proof of a quantitative method is a challenging task for several reasons [BLESSING, 2004]. Another aspect which complicates the assessment of method application is given by the period of time. The only way to identify the usefulness of a method is the qualitative description of all process steps during the research [EHRLENSPIEL, 2003]. According to Ehrlenspiel [EHRLENSPIEL, 2003] during the introduction of methods their positive effect must be determined, for example, by a comparison of the suggested solutions, developing time and the number of the necessary changes or complaints before and after. To make the results and benefits of the new approach and method developed in this work measurable there are measurable criteria as *monetary (quantitative)* as well as *non monetary (qualitative)* goals defined [KRAHE, 2004] defined. Monetary goals are measurable, for instance time, the sequence of method, design data quality and costs. Non-monetary goals like usability, designer satisfaction and motivation are not easily measurable but this can be done by empirical studies, for example by carrying out a questionnaire or interviewing designers about the aspects mentioned above after the application of the method. The next section will explain the second step of the approach according to Blessing and Chakrabarti which is the Descriptive Study I together with the identified factors and indicators which are important during the design process.

2.3.2 Descriptive Study I

The next step after the description of the research criteria is the Descriptive Study I. Furthermore this section describes the main characteristics of empirical-descriptive methodologies in design research and shows the significant attributes. Therefore, this section of the work will handle and explain in detail the different methods and possibilities of descriptive studies (for instance observations, questionnaires, interviews, and experimental methods), which are very important approach for investigating design methodology. The focus of descriptive methodology is to investigate the processes and methodologies which are used in design development. One of the characteristics of descriptive methodologies is that they do not define a certain hypothesis about the so-called “right” procedure [BAYA, 1996]. Descriptive methods analyse and describe the current situation [BAYA, 1996]. The approaches which have been selected for the Descriptive Study I of the following thesis are a) carrying out a questionnaire between designers in power train development b) interviewing CAD experts and coaches and c) investigation of existing PA CAD parts and assemblies. Chapter five will present the results of the Descriptive Study I.

There is a lot of relevant work about descriptive design research methods. For example Baya [BAYA, 1996] investigated in 1996 the development process and activities of designers in nuclear power engineering. The goal of this investigation was to collect ideas and improvements of methods in the problem-solving-process. He observed 50 designers during their daily work. He analysed the results of the methods used in the design process and created new methods for the designers. According to Baya [BAYA, 1996] descriptive studies present a step by step method and tend to offer a characterisation, description and understanding of what happens during the design process. These studies are based on a profound analysis of design action and activities. Much design research is based on descriptive studies and there are also some methods developed to collect design data by means of design experiments. After the collection of data the results get analysed to obtain knowledge and understanding of certain design behaviour. This point also helps to create a better understanding of problems during the design process and is used to change design processes or to develop for instance methods of enhancing design tasks. Baya [BAYA, 1996] explained that there are different empirical methods which can be used for investigating design activities. Table 1 describes the different empirical methods with their advantages and disadvantages [BAYA, 1996].

Empirical Method	Appropriate Scenario	Advantages	Disadvantages
Deposition: timely interviews during the process (can also be used with verbal protocol)	single designer	- targeted data capture - easier analysis - can study long tasks - data is chronological	- interferes with design process - incomplete data capture
Verbal Protocol: designer talks out loud during design to externalize thinking process	single designer	- access to designers thoughts - comprehensive data capture - data is chronological	- difficult and time consuming analysis procedure - can only study short tasks - verbalizing may interfere with design process
Discussion protocol: natural communication among team members	small team	- no interference with design process - can study communication, negotiation and such	- difficult and time consuming analysis - incomplete data capture - can only study short tasks
Retrospection: interviews or questionnaire after the design process	single or small team	- no interference with design process - targeted data capture - easier analysis	- data collected is not chronological or real-time - partial data capture
Participant observer: observer is also a member of the design team	small or large team	- can study very long tasks - no interference with design process - data is chronological	- difficult and time consuming analysis - incomplete data capture

Table 1: Empirical design research methods [BAYA, 1996]

According to Blessing/Chakrabarti [BLESSING/CHAKRABARTI, 2002] descriptive studies can be created by design researchers from the different aspects determined in the design of the study. To identify the most suitable options it is very important to pay strong attention to the formulation of the focus of the research study. The focus can be [BLESSING/CHAKRABARTI, 2002]:

- the aim of the research;
- the specific research questions;
- the specific research hypotheses, model and theory;
- The various constraints that are outside the researcher's control.
- Alternative, contradictory hypotheses, models or theories can be included if the aim is to find the best amongst them.

Descriptive studies have different aspects and options [BLESSING, CHAKRABARTI, WALLACE, 1998]: The most important aspects of descriptive studies are: environment, nature of the study, data collection methods, subjects, number of cases, team size, time constraint, duration, continuation, role of researcher, contribution of the researcher in the process and the results of the observed part of the processes like drawing or prototype. Table 2 shows the different aspects and options of the characteristics of descriptive studies [BLESSING, CHAKRABARTI, WALLACE, 1998]:

Aspects	Options
Environment	Where the study took place: lab or industry
Nature of the study	(comparative) exploratory, (comparative) action research
Data collection methods	Pure observation, thinking aloud, introspection, participant observation, diary keeping, archival research, questionnaire, interviews
Subjects	Level of experience
Number of cases	the number of data sets collected, e.g. the number of experiments or interviews conducted
Team size	number of subjects involved in each case
Time constraint	Any limits to the design time imposed on designer
Duration	Length of process studied
Continuation	Is the process observed continuously
Role of researcher	Contribution of the researcher in the process and the outcome
Required results	Results of the observed part of the process: e.g. specification, layout drawing, prototype, product
Design object type	Original, variant, redesign

Table 2: Characteristics of descriptive studies [BLESSING, 1998]

All of the above-mentioned options are interconnected, for instance the decision to do research in industry will increase the number of possibilities which are available for collecting all the data [BLESSING, 2004]. Many options are acknowledged and tested by Blessing and Chakrabarti. They recognized that it is very important to show and investigate the possible options clearly so that the context of the research study can be determined [BLESSSING, 2004]. Cross [CROSS, 1997] stated that very good designers *"spend the major part of the available time to reaching an understanding of the design problem and the potential solution"*. This aspect shows that at first it is very important to identify the real research problem before generating different solutions. The results of detailed descriptive studies are based on a small number of case studies. Furthermore, in the Descriptive Study all the collected data can be analysed in different ways. But the analysis of the collected data is one of the most important points that have an effect on the general validity of the findings [DWARAKANATH et la, 1995]. Therefore, it is essential to document how the collected data is investigated. The main task of Descriptive Study I is to analyse the current situation of the design methods and processes. The importance of descriptive studies is to increase the understanding of design in order to inform the development of design support [BLESSING, 2004]. The role of the Descriptive Study I stage is [BLESSING/CHAKRABARTI, 2002]:

- To identify the factors that influences the formulated measurable criteria.
- To provide a basis for the development of support to improve design.
- To provide more details that can be used to evaluate developed design support.

Descriptive Study I involves studying design activities and processes in order to improve the understanding. The focus can be on products or methods as well as on the process of designing.

The next section will explain the main task of the Prescriptive Study.

2.3.3 Prescriptive Study

After the Descriptive Study I the next step is the Prescriptive Study. The characteristics of the Prescriptive Study stage in the DRM are that it describes the developed solution approach which is based on the findings in the Descriptive Study I. Prescriptive design studies create results from a process and the procedure of doing design. These methods are normally developed by analysing and hypothesizing in relation to the whole design process [BLESSING, 2004]. The main characteristic of such methods is that they recommend systematic or “algorithmic” methods. A research process guarantees that results are achieved and decisions are made after all required and essential information has been created, consequently no significant elements of the “problem of design” are disregarded [BLESSING, 2004]. Such methods highlight the requirement of analytical effort before creating new design methods and proceeding to the next step. It is mainly prescriptive models, which handle iterations and reactions which happen among different design steps. Related to the following thesis the developed PA solution approach of the Prescriptive Study will be explained in Chapter Six.

2.3.4 Descriptive Study II

According to Blessing [BLESING/CHAKRABARTI, 2002] the Descriptive Study II is used to test and analyse the new methods and tools which have been developed. The Descriptive Study II can be used to answer questions about effectiveness, impacts and side-effects of the newly-developed method. In the research the author made a comparison between the CAD designer groups who worked without the developed PA approach ("old" referenced model; definition of the "as is" process and method) and the CAD designer group who worked with the developed PA approach ("new" developed method; definition of the "to be" process and method). This section will present some examples and case studies in the automotive industry which have been accomplished to demonstrate the changes and possible improvements through the PA method application. The Descriptive Study II will use the same research methods as Descriptive Study I. Aspects that should be considered in preparing an assessment are: (a) need, (b) conceptualization and underlying assumptions, (c) implementation and introduction, (d) impact: desired and undesired, indirect and direct, immediate and long-term, (e) efficiency, (f) users and their behaviour, (g) organizational, technical and other contextual prerequisites [BLESSING/CHAKRABARTI, 2002]. During the quantitative evaluation of the PA approach it was very important to demonstrate whether the identified indicators and factors were significantly changed or not. In Chapter Eight the results of the Descriptive Study II will be explained and discussed. Furthermore the Descriptive Study II in Chapter Eight will present approaches which enable a quantitative and qualitative evaluation of the developed PA approach.

2.4 Qualitative and quantitative evaluation approaches and indicators

This section of the work describes the important aspects and characteristics of qualitative and quantitative research studies. The main methods used for monitoring and evaluation come directly from social science research methods and can be divided into:

- ***Qualitative methods*** are in-depth case studies, questionnaire surveys, rapid assessment, and participatory assessment [DALE, 1998]. The characteristics of a qualitative study are that: (a) it generates ‘working hypotheses’ that can be further examined through quantitative research with specific pre-defined questions; (b) it assesses how important the average is at the local level (c) explains trends and patterns emerging from survey; (d) triangulates (verifies or refutes) survey results; and (e) enriches analysis of trends, patterns emerging from the survey through new learning or taken for granted [DALE, 1998]. Furthermore from the ´Dales´ view the qualitative evaluation can be used to get information from those who are studied to speak for themselves, to provide their perspectives in words and other actions. Therefore, qualitative evaluation is an interactive process in which the persons studied teach the researcher about their lives. It is also possible to evaluate and understand the experience of the participants with subjects. Qualitative methods imply a direct concern with experience as it is `lived' or `felt' or `undergone' [REICHARDT, 1979].

- ***Quantitative methods:*** Quantitative methods produce data in the form of numbers while qualitative research tends to produce data that are stated in prose or textual forms [REICHARDT, 1979]. The key characteristics of quantitative approaches are [DALE, 1998]: a) Control of the activities: This is the most important element because it enables the scientist to identify the causes of his or her observations. Experiments are conducted in an attempt to answer certain questions. They represent attempts to identify why something happens, what causes some event or under what conditions an event occurs. Control is necessary in order to provide unambiguous answers to such questions; b) Operational definition: This means that terms must be defined by the steps or operations used to measure them. Such a procedure is necessary to eliminate any confusion in meaning and communication; c) Replication: To be replicable, the data obtained in an experiment must be reliable; that is, the same result must be found if the study is repeated. If observations are not repeatable, our descriptions and explanations are thought to be unreliable.

The review and study of the evaluation research literature shows that there is a discussion over the relative usefulness of qualitative and quantitative methods for conducting evaluations. This is despite the fact that some have not acknowledged that this debate has been going on for some time - ‘there is, indeed, a disagreement over whether or not there is a disagreement’ [COOK, 1978]. Cook [COOK, 1978] argues that the debate between the advocates and defenders of qualitative and quantitative evaluation has been framed

within two different paradigms, that is, two different ways of conceptualizing and understanding the world and social interactions. They argue: *"that defender of the qualitative methods usually subscribe to what they call the qualitative paradigm, 'a phenomenological, intuitive, holistic, subjective, process-oriented and social anthropological world view' while defenders of quantitative methods subscribe to the quantitative paradigm which, in contrast, 'is said to have a positivistic, hypothetico-deductive, particularistic, objective, outcome-oriented, and natural science world view"*.
According to Carvalho [CARVALHO, 1997] during the consideration of "*ways to join "quantitative" and "qualitative" approaches and data, it is important to be aware of their comparative advantages and to recognise that 'strong fences make good neighbours". In short, while quantitative methods produce data that can be aggregated and analysed to describe and predict relationships, qualitative research can help to probe and explain those relationships and to explain contextual differences in the quality of those relationships"*. With this recognition that qualitative and quantitative methods and data are often more powerful when combined, at different levels and in different sequences, we can categorize different ways of combining and sequencing. Carvalho [CARVALHO, 1997] usefully describes ways of combining the best of qualitative and quantitative approaches: (1) integrating methodologies for better measurement; (2) sequencing information. Furthermore it is quite important to identify indicators which should be evaluated. This is one of the most important and also one of the most challenging parts of the evaluation process.

2.5 Conclusion

This chapter has presented a number of relevant works related to research methodologies (Kolb's Learning Cycle, Duffy and Andreasen's Framework and the Blessing/Chakrabarti DRM approach). All of the presented approaches are valid and have their advantages and disadvantages. For example the approach according to Kolb [KOLB, 1984] is less relevant for the present work in view of the following weaknesses: (a) it pays insufficient attention to the process of reflection; (b) the model takes very little account of different cultural experiences/conditions; (c) the idea of stages or steps does not sit well with the reality of thinking; (d) empirical support for the model is weak and (e) the relationship of learning processes to knowledge is problematic. The approach according to Duffy and Andreasen [DUFFY/ANDREASEN, 1995] which contains four steps (Reality→Phenomenon model→Information model→Compute model) is also difficult to apply in the present work. The reason is that this approach does not explain and elaborate the relevant criteria and indicators for the research aim and purpose. From the design research perspective methods are necessary which are able to assist reflection on the situation before and after the solution process. That means for example how is it possible to identify challenges and difficulties of the current design process and what kind of solution approach is necessary. At the end of the process it should also be possible to demonstrate the changes or possible improvements through the application of a certain solution approach. In general following aspects have not been considered in the approaches according to Kolb and Duffy/Andreasen:

- There is no established method of doing design research.
- There are only partial approaches to design research, like making observations and experiments. This partial approach does not consider the whole research process.
- There are limited links between factors which have influenced the design process and the success of implemented improvements.
- There are not sufficient methods with which compare the situation before and after the design research.

The next approach which has been identified is the Design Research Methodology (DRM) according to Blessing and Chakrabarti [BLESSING/CHAKRABARTI, 2002]. By means of the approach according to Blessing and Chakrabarti [BLESSING/CHAKRABARTI, 2002] it is possible plan and carry out the research. Furthermore it is possible to identify the criteria which are important during the design with PA CAD systems. The Descriptive Study I offers methods which enable the researcher to analyse the important issues and problems during the design process with PA CAD systems. Furthermore based on the results of the Descriptive Study I it will be potentially possible to present a method for PA CAD systems in the Prescriptive Study. The impact during the implementation and evaluation of the developed PA approach will be presented in Descriptive Study II by means of different evaluation approaches. Because of the advantages and clear method of how to do design research the author decided to apply the DRM approach according to Blessing and Chakrabarti.

3 Parametric design techniques

The Development of Computer Aided Design (CAD) systems started as early as the 1960s, its progress was severely hampered by the capability of the computer at that time. A decade later, CAD development and implementations began to enter the commercial market. Initially, with 2D in the 1970s, it was typically limited to producing drawings similar in to hand drafted drawings. Advances in programming and computer hardware, notably solid modelling in the 1980s, allowed more versatile applications of computers in design activities. Key products at that time were solid modelling packages. Among them were Romulus and Uni-solid based on PADL-2 and the surface modeller Catia; all were released in 1981. The next milestone was the release of ProEngineer in 1988, which heralded more usage of feature based and parametric modelling methods linking the parameters of features [XU, 2009]. The bulk of the development in commercial CAD systems has been in modelling the form of products, for example in providing techniques to assist in the representation of form using conventional drawings or new modelling techniques. The driving force behind CAD has been the desire to improve the productivity of the designer, automating the more repetitive and tedious aspects of design and also to improve the precession of design models. New techniques have been developed in an attempt to overcome the perceived limitations in conventional practice – particularly in dealing with complexity – for example designs as complex as automobile bodies or engines [ROLLER, 1990]. Therefore CAD therefore should enable the designer to tackle more quickly and accurately, or in a way that could not be achieved by other means. It must also be stressed that at present CAD does little in helping a designer in a more creative and intuitive way such as generation of possible design solutions, or in those aspects that involve complex reasoning about the design. However, the modern CAD systems present little robustness and flexibility in terms of working with or reusing of created CAD created components. The early CAD tools were primarily based on building geometry with specific dimensions and creating geometry with specific initial relationships to existing geometry [ROLLER, 1990]. This chapter will define important aspects related to 3D modelling of engineering artefacts using parametric design techniques. These techniques are parametric, variational, feature based and history-graph based design. At first the author will define and explain the different characteristics of the above mentioned [ROLLER, 1990].

3.1 Parametric Design

Parameter is a term that has many definitions depending on the use. Therefore this section of the work will give some different definitions of the term parameter and parametric design which are used in different domains. The term parameter comes from mathematics and it refers to a factor that controls the values of other factors with respect to a linear relation [ROLLER, 1990]. In computation, a parameter is the argument or series of arguments of a function with takes values as inputs. A parameter is also the placeholder for the value of a variable [HERNANDEZ, 2006]. The Random House dictionary defines parameters from different aspects such as mathematics (a constant or a variable term in a function that determines the specific form of the function but not its general nature), statistics (a variable entering into the mathematical form of any distribution such that the possible values) and determining factors. In design a parameter is an entity that can hold a value to control geometrical components or relations between geometrical components [SHAH, 1993]. Parameters are used to substitute specificity for generality. In CAD, geometrical models are constructed in very specific ways [HERNANDEZ, 2006]. Parametric design implies the use of declared parameters to define a form. This requires rigorous thought in order to build a geometrical model embedded in a very sophisticated structure appropriate for the needs of the designer. Therefore the designer must anticipate which kinds of variations he might want to explore in order to determine the kinds of transformations. According to Shah [SHAH, 1993] “parametric systems” solve constraints by applying sequential assignment to model variables. Each assigned value is computed as a function of the previously assigned values. Figure 7 shows an example of PA CAD design of a piston.

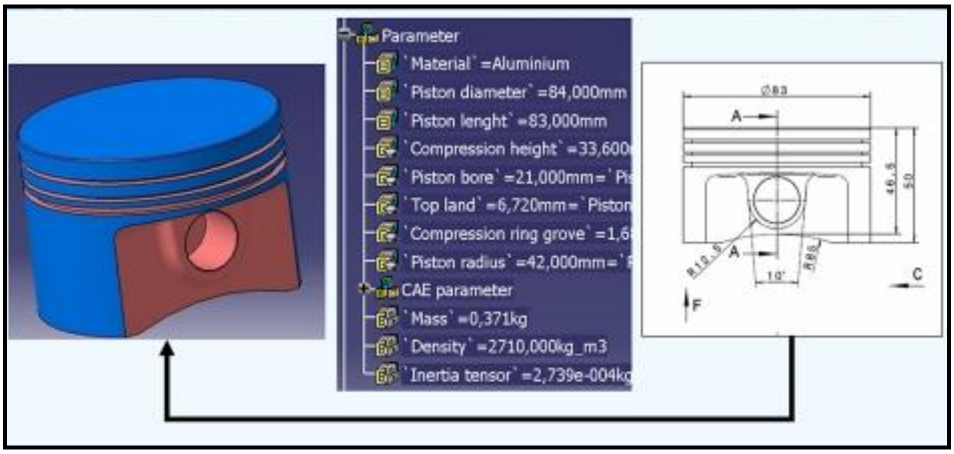


Figure 7: PA design of a piston

Furthermore a “parametric problem” can be described in terms of a list of variable entities, parameters describing the entities, relationships between the entities and/or parameters and the allowable range for each parameter. Shah distinguished two kinds of parameters in geometrical modelling, explicit and implicit parameters [SHAH, 1991]. Geometrical models with explicit parameters have fixed attributes, for this reason, in order to execute any kind of changes of the CAD-model, it is essential to delete and recreate the geometrical CAD-components. Modification of the geometry can only be made when a special shape is exactly replaced by a new shape [SHAH, 1991]. Implicit parametric CAD-models are labelled by having certain attributes that make modifications possible without deleting and recreating any of the metrical components. For that reason variations are accomplished by modifying the values of the parameters [SHAH, 1991].

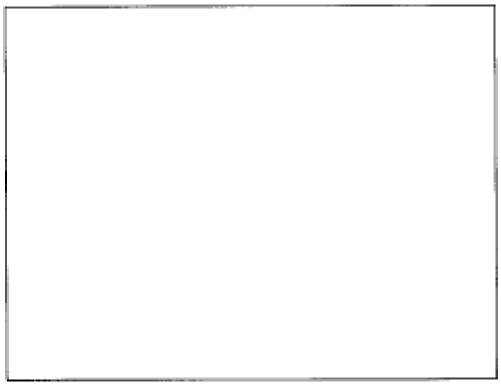


Figure 8: Explicit parameters

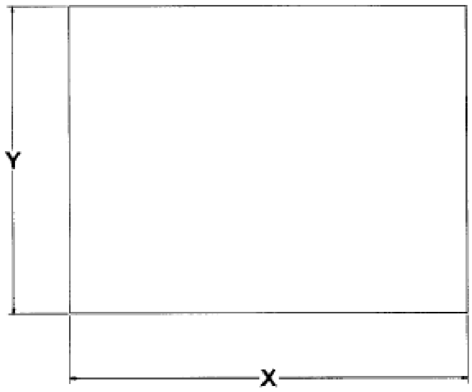


Figure 9: Implicit parameters

Figure 8 and 10 demonstrated different examples for explicit and implicit parameter and its characteristics:

- Explicit model of a rectangular shape. To perform variations it is necessary to erase and redraw a new rectangle [HERNANDEZ, 2006] (see Figure 8 and 10).
- Implicit model of a rectangular shape. Note how the length and height attributes are parameterized by the X and Y parameters. The size of the rectangular shape can be altered by changing the values of the X and Y parameters, therefore to perform variations the parameters [HERNANDEZ, 2006].

Furthermore according to Shah [SHAH, 1991] there are different criteria which are important during the classification of parameters in context of STEP standards. The following list shows these [SHAH, 1991]:

- Criterion 1 (numeric vs. non-numeric): The dimensional characteristics of a feature can be given explicitly as numerical values, but other properties can be specified non-numerically. For example, a cylindrical “hole” feature may be provided with an enumerated choice of flat, hemispherical or conical bottom surface.
- Criterion 2 (bound vs. unbound): A bound parameter is associated with (or bound to) an attribute of some instance whose value is potentially variable following the exchange. An unbound parameter is not directly associated with an attribute in that manner, but participates in a specified mathematical relationship that may control the values of one or more bound parameters [KIM, 2008].
- Criterion 3 (dimensional vs. non-dimensional): A dimensional parameter, which represents a dimension explicitly, is created when the designer uses a ‘dimension command’ as provided by the CAD system user interface. Explicit dimensions are usually associated with sketch construction, whereas feature creation operations usually give rise to implicit dimensions (see below). Some CAD systems distinguish between dimensional parameters, which they refer to simply as dimensions, and non-dimensional parameters, which they refer to as parameters.
- Criterion 4 (dependent, independent, free): A dependent parameter is one whose value is governed by a constraint and can only be changed by modification of independent elements in that constraint. An independent parameter is one whose value is editable and can be used to govern the values of other elements in a constraint. A free parameter is one that is associated with some attribute of the model but is not involved in any constraint.

The above mentioned aspects of the different kinds of parameters and their criteria demonstrate that parameters in CAD modelling are very multifarious and therefore the required and created parameters have to be identified, determined and represented during the design process with PA CAD systems. One of the most significant challenges during the modelling and design process of many PA CAD systems is that designers have problems to identify and determine the different kinds of “parameters” and their relationships to each other. Therefore designers have difficulties catching the so called “design intent” of the created CAD parts and assemblies. Furthermore current parametric CAD systems offer the opportunity to create different kinds of relationships between parameters. According to VDI 2209 there are three different kinds of relationships which can be created between the geometrical entities. These are relationships are arithmetic, logical and geometrical [VDI 2209, 2006]. The definition and characteristics of the different kinds of relationships are defined as f0llows:

- *Arithmetical relationships:* In every parametric CAD system it is possible to define basic arithmetical relationships. The relationships are operations like addition, subtraction, multiplication etc. Furthermore many parametric CAD systems offer the opportunity to use predefined mathematical functions like sin, cos or radical etc [VDI 2209, 2006].
- *Logical relationships:* This kind of relationship (bigger than, smaller than, AND, IF, OR etc) can be defined in relation to different kinds of operations (if-then-else etc) to represent different modelling situations and cases. For example the breadth of a chamfer c of an axle can be defined in relation with the diameter of the axle [VDI 2209, 2006].
- *Geometrical relationships*: These kinds of relationships are the conventional relationships which can be defined to describe the constraints (horizontal, vertical, parallel etc.) between the geometrical entities like lines, curves or circles on a 2D sketch [VDI 2209, 2006].

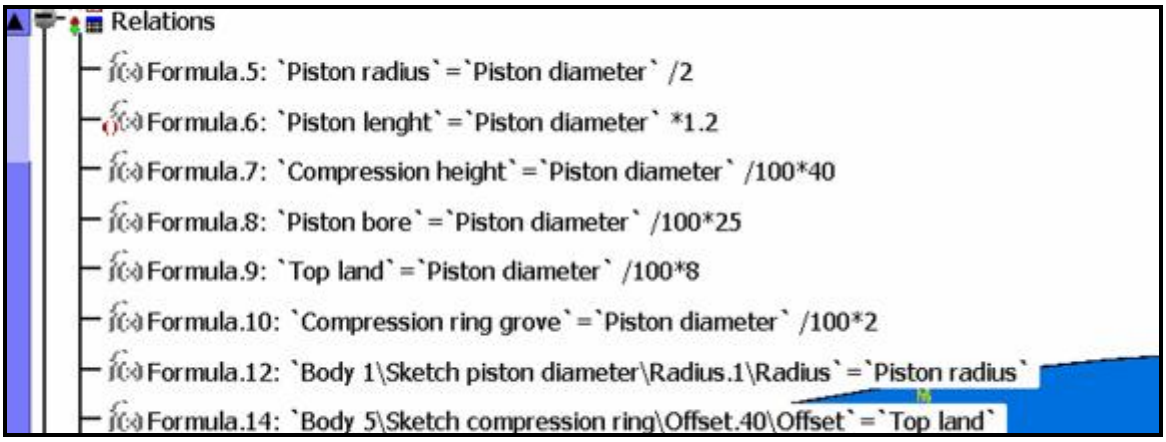


Figure 10: Arithmetical relationships between parameters

Figure 10 shows an example which demonstrates the defined relationships between parameters during the design process of a parametric piston. This example demonstrates that one of the disadvantages of PA CAD systems (in this case CATIA V5) is that it is very difficult and time consuming to understand, identify and determine the complex relationships between the chosen parameters. A parametric CAD-model is labelled by having certain attributes that make modifications possible without deleting and recreating any of the components. For that reason variations are accomplished by modification of the values of the parameters. Therefore, to accomplish modifications it is not necessary to delete and recreate the geometry. The above mentioned definitions consider only the term 'parameter'. But the process of parametric design has to be considered separately [HERNANDEZ, 2006]. Parametric design can be defined as the process of designing with parametric CAD models in a certain environment where variations are easy, as a result substituting singularity with diversity in the design process [SHAH 1991]. In the context of design engineering a parametric design includes the application of accounted "parameters" to describe a geometrical shape or form. In this case a very exact consideration of creating the parameters to construct a geometrical CAD-model is necessary. Furthermore CAD designers must be able to know which variations of the geometry might be possible and what kind of changes the parametric model will have. The process of "parameterization" can be explained as a process of definition and execution of attributes (parametric) which describe the geometrical model. To be able to parameterize a CAD model, it must have certain geometrical characteristics (tangencies, parallelism, etc.) and dimensions defined (either explicit or implicitly) that make it susceptible to having geometric relationships established. Different aspects of a parameterization can be considered [SHAH 1991] as follows:

- The moment of parameterization, this can occur during or after design. Post-design parametric is an approach that makes existing databases more valuable because of the ability to create a parametric program from an old model. If parameterization takes place during the design process it is desirable that this parameterization is fully modifiable.
- Extent of parameterization: the whole model or model partially parameterized. In certain applications only a subset needs parameterization, so this capability seems desirable.
- Mode of parameterization: manual or automated. When automated, the process may be fully automated or assisted, offering suggestions.
- Control of the parameterization: when using automatic parameterization, there exists a capability to enable or disable it and to modify constraint priorities (switch to high, low or off). If this capability is not present, there will be no control over erroneous constraint assumptions made by the system.
- Level of constraint definition: Under constrained models: lack enough dimensions, constraints or rules. A degree of freedom analysis is required to identify the remaining constraints needed. Some systems highlight the geometry that is not

fully constrained; others report the number of degrees of freedom remaining in the model (with each degree of freedom corresponding to a missing constraint).

Related to the above mentioned aspects Vajna states explicitly that before starting to design and create the parameters it should be clarified what kind of parameters exist and are required. In this way designers get a better understanding of the parametric CAD models and assemblies which should be created and generated [VDI 2209, 2006]. Furthermore it is also important to be able to represent the relationships between the different kinds of parameters. PA CAD design “forces” designers to work in a methodological and structured way so that a clean documentation of the created parameters and their relationships to each other is required [XU, 2009]. In this case many CAD systems have weaknesses in their ability to clearly show and represent the “design intent” of the associated parametric CAD models clearly and in a not misunderstood way [XU, 2009]. Xu suggests that there is a certain “front-thinking” necessary to get a better understanding of the created parameters and associative relationships. These kinds of CAD systems should be able to represent designers’ intentions and without any additional effort regarding the created relationships created between the geometrical, physical and process related parameters (i.e. parameter interrelationship plan). Figure 11 shows the different approaches during the definition of relationships between parameters by means of two currently available CAD systems, Pro Engineer and CATIA V5.

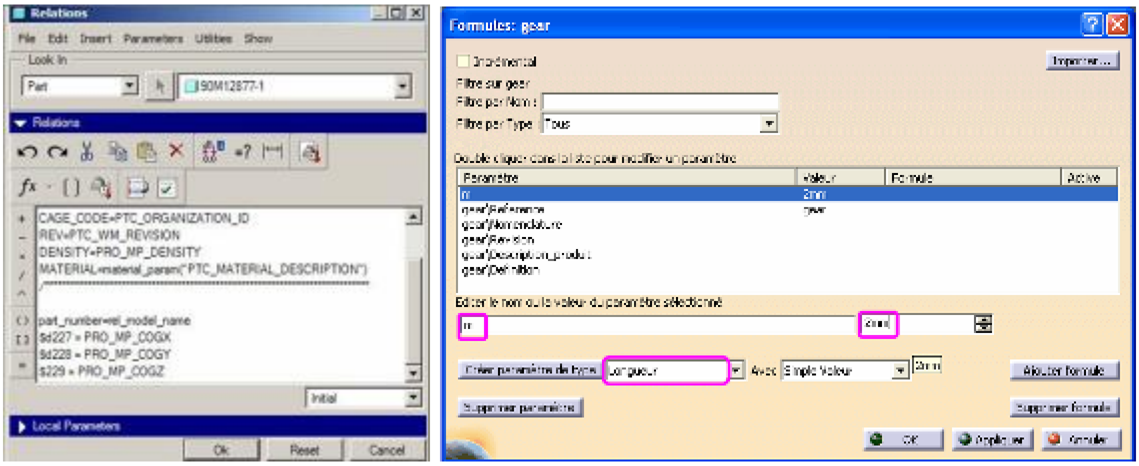


Figure 11: Parameter relation definition in Pro/E (left side) and Catia V5 (right side)

During the creation of the parameters and the relationships between the parameters it is important that a certain methodology is available which helps designers to identify, determine and represent the different kind of parameters. Before starting to create the parameters it is very important that the structure of the different kind of parameters is well planned [AIT, 1995]. That means which parameters are necessary for the definition of the CAD models and which kind of relationships between the parameters should be clarified. The structure of the parameters should be kept simple so that only the important “key parameters” are available. The identification of the “key parameters” can be one of the most important aspects because normally these kinds of parameters “drive” and “steer” the other parameters, for that reason methods are necessary which should help to identify these key parameters. This is also one of the targets of the following work, to elaborate solutions which make the definition, determination and relationships of different kinds of parameters easier and in a better way.

3.2 Associative Design

Related to the design process, associativity describes the fixed relationship between geometrical entities and objects. These associative relationships include for example the connection of two different 3D CAD models or the connection of 3D CAD models and downstream process related elements such as finite element models, toolpaths and other derived information. In an associative system, any modification in a 3D model is automatically propagated to down-stream applications and connected geometries [AIT, 1995]. Normally in parametric CAD, designers are able to describe a geometric feature with several parameters. Moreover the designer is able to modify the geometry by changing the geometrical parameter values instead of deleting geometric entities. Associative environments enable CAD designers to maintain the relationships between geometrical objects, features and diverse design process steps for instance linkage between the CAD model and FEM model or CAD drawing) [AIT, 1995]. Figure 12 shows the associative connection between two different CAD models.

The first CAD model I represents an Adapter and contains the basic geometrical entities, in this case the Adapter model (CAD model 1) contains a rectangular shape. Furthermore this shape is used in CAD model 2 which represents a block (solid). The geometry of the block is linked and is based on the shape of the Adapter model (CAD model 1). In the case of geometrical changes to the Adapter model (changed situation 2: the length and width of CAD model 1 are modified) the geometry of CAD model 2 is changed and generated automatically.

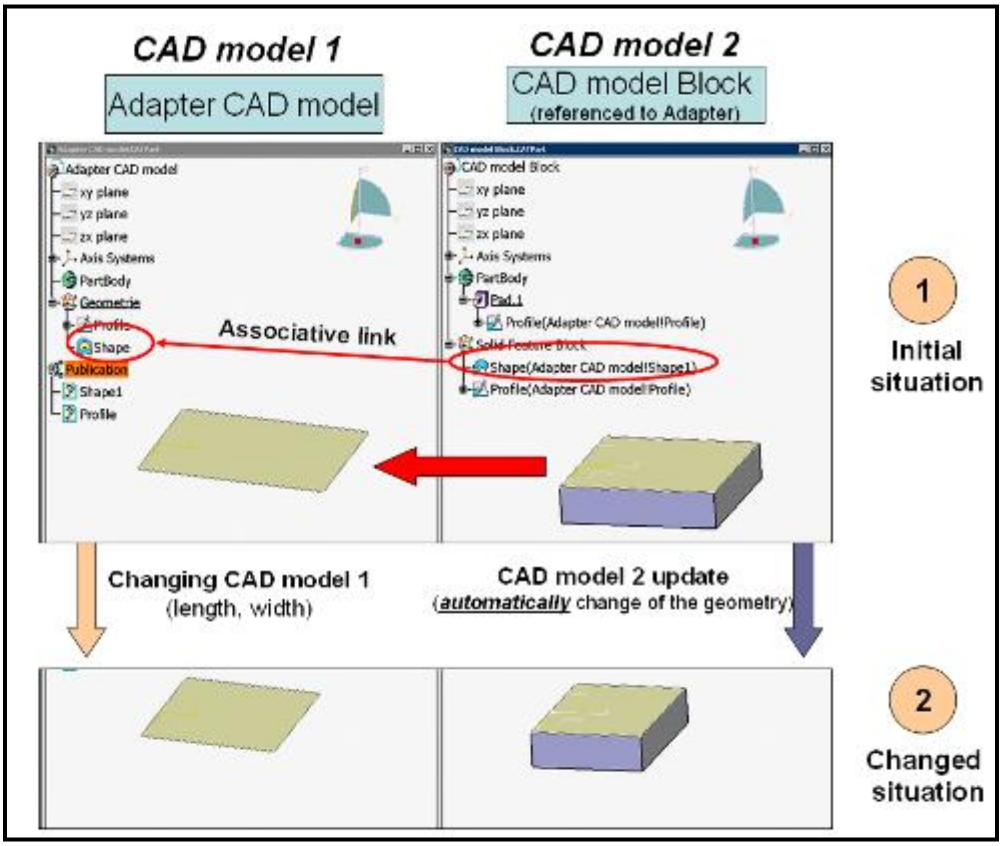


Figure 12: Example of associative relations

The next section will explain the history based-modelling design.

3.3 History-Based Modelling

Besides the geometry, most CAD systems are able to keep the history or “procedural data” about the creation of the CAD design model. When this type of data is also captured and modelled together with the geometric information of a design, it may be called a history-based approach to CAD [XU, 2009]. In a history-based CAD system, subsequent geometry is built upon the previous. According to Monedero [MONEDERO, 2010] the commercial parametric modellers available at the present time use a data structure that keeps track of the sequence followed to create a model. Any operation, together with the data used to complete it, is recorded in the order that it occupied during the process of building a particular model. The operational parameters can be geometric entities as well as expressions [MONEDERO, 2010]. The model can be modified by substituting the data used in a particular operation. Recomputing the model will have the effect of changing some of its geometric characteristics while maintaining the connections, that is, the intended relations between the different entities [MONEDERO, 2010]. All geometries are often controlled by parameters, which comprise constraints and relationships. The history of the created geometrical entities and parameters can be used to generate new geometrical entities by changing parameters and “regenerating” the whole history of the part. During the design process of building a CAD part, the designer can roll back to check the created features at an earlier stage. Figure 13 presents the history tree of different parametric CAD systems.

A history based model may exhibit some intelligent nature [AIT, 1995]. For instance, a designer might identify that a hole should be created in the centre of a square shape pocket product. He located it half-way from each side of the pocket. No matter what size the pocket may be changed to, once the history graph is replayed the hole always has its desired position in the centre of the pocket [AIT, 1995]. It can be compared to building a house of cards. In this analogy the “cards” would be modelling features that are interrelated in the history tree. When an original designer predicts all possible future changes with them in his mind, it is not a problem to later arrange a card or pull one out to modify the model [XU, 2009]. That means that the designer has a lot of “front-thinking” to do. But foreseeing all possible changes is not always an easy task. With insufficient design foresight, pulling a card would affect relationships to such a point where the model is no longer stable and may fail to regenerate [XU, 2009]. This aspect makes it very clear that without a plan or a methodological approach on how to manage the dependencies and relationships between the parameters and the corresponding associative relationships inside and outside of the CAD model it will be very difficult to modify the created geometrical components created later in the process. Furthermore because of the dependencies between the features in the history tree, designers need to have a clear understanding of the PA CAD parts created.

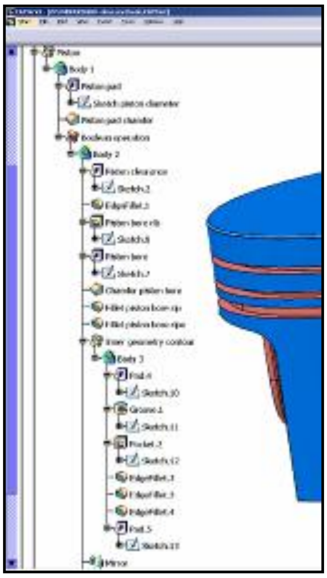


Figure 13: History tree of CATIA V5

This means that a certain methodology is necessary to support the "front-thinking" process which should help to identify, determine and represent the interrelationships of the created parameters and their associative relationships. According to Xu [XU, 2009] in history-free CAD systems, an operator builds all components, parts and assemblies in one common workspace. Furthermore multiple parts and assemblies can be loaded at the same time and a single command may allow users to arrange parts in a subassembly or move subassemblies within a top level assembly [XU, 2009]. The advantages of history-based CAD systems are that parts of the "design intent" can be captured in a history-tree recipe using relationships and constraints. Furthermore history-based CAD systems are better for the type of products involving large families and similar parts in which for example only sizes change. History-based CAD systems have been established in the marketplace because they let users modify designs in a highly predictable way. 80 to 90% of a new product is simply reused components. For example in the automotive industry if a valve is modelled, designers can tweak sketches or parameters and regenerate a new valve [XU, 2009].

3.4 Variational Design

The terms “parametric” and “variational” have been used almost interchangeably in technical and particularly commercial context. From the viewpoint of the end user, the two types of systems are similar to the extent that it is not always straightforward to determine from the outside which type of systems is used [SHAH/MÄNTYLÄ, 1995]. Variational design geometry is able to recompute the current situation, independently of the sequence that has been followed to achieve this situation [SHAH/MÄNTYLÄ, 1995]. The variational method is based on the description of parameters by dint of mathematical equations and the possibility of a variational system which is able to find a solution for them. Shah and Mäntylä [SHAH/MÄNTYLÄ, 1995] described that variational systems solve constraints by constructing a system of equations representing the constraints, and solving all constraints of the system simultaneously on the basis of a numerical equation-solving procedure or some equivalent method. Such method has advantage, because it is independent of the way the CAD-model has been modelled and is also able to accept any situation or any model as input. Dimensions are considered as constraints that affect a particular set of points in the model. According to AIT [AIT, 1994] a variational system is one in which a number of objects has properties which have certain rules governing them. These rules stipulate the ways in which they relate to other entities. Furthermore, the set of constraints can be solved, returning versions of the objects whose properties obey the constraints. This solution is done simultaneously, with the constraints allowing bidirectional dependency. The following example should help for a better understanding of parametric and variational design. These two different respective forms are defined:

Case 1: $y = a^3 + b^2 + c$^ → **Case 2: $ay^3 + by^2 + c = 0$**

In case one an explicit equation can be used directly to compute the value of the variable y, given the parameter a, b and c. Parametric systems can work by scanning the constraints and applying predefined solution methods such as case number one. On the other hand an implicit equation such as case two needs to be solved for y. As in this case multiple solutions are possible. Being based on explicit constraints satisfying parametric models can be evaluated rapidly. While variational models using implicit constraint satisfaction techniques can deal with coupled constraints, they are slower and more limited in their capability.

3.5 Parametric Feature Based Design

Shah and Mäntylä [SHAH/MÄNTYLÄ, 1995] defined that feature modelling is an approach where high level modelling entities termed "features" are utilized to provide a base for linking the design rationale with the model, hence supporting reuse of information. According to VDI 2222 [VDI 2222, 1999] features are used in design, manufacturing, assembling, quality management and controlling. Therefore it is also not very easy to give a clear definition of the term "feature". The different usage of the feature technology leads to a differentiation concerning feature definition [VAJNA, 1998]. There are many definitions of feature and in this section the author has chosen only some selected definitions which seem to be suitable in context of this work. Shah and Mäntylä [SHAH/MÄNTYLÄ, 1995] defined that features represent the engineering meaning or significance of the geometry of a part or assembly. Furthermore features can be thought of as building blocks for product definition or for geometric reasons. Features can be categorized as follows: (a) A feature is a physical constituent of a part (b) A feature is mapable to a generic shape (c) A feature has engineering significance. (d) A feature has predictable properties. The working group FEMEX (Feature Modelling Experts) [FEMEX, 1997] defined features as "an aggregation of geometry elements and/or semantics". Rude and Pratt [RUDE/PRATT, 1991] defined features as a region on the surface of a part. Anderl [ANDERL, 2007] described features as a collected quantity of geometry elements with the task to describe the embodiment zones. Furthermore it can be seen as constituted by a set of:

- Geometric elements which define the geometrical shape
- Parameters which define the positioning and dimensions
- Constraints which represent relations between the feature and its environment
- Attributes which attach other information associated to the feature to complement its description, adding data required for its use in downstream applications (material, tolerances, surface finishing, etc.).

When classifying features [AIT, 1995], various criteria can be followed, among them one can mention the manufacturing technologies involved (sheet metal, composites or milled parts) or the product development phase (conceptual design, detailed design, manufacturing, etc.). However, a more general way to classify features is taking into account the information structure defining the product. Inside the level that features represent in this product structure, at least two sub-levels can be distinguished. In the lower, we can find Basic features, which are constituted only by geometric elements, parameters, constraints, etc. A typical example is a 'hole' a scheme of which can be seen in Figure 14. Compound features are situated in higher sub-levels. These compound features are built up by the same type of constituents as the basic ones but also hold other features, basic or compound. An example can be a group of holes arranged in a certain pattern (see Figure 15) [AIT, 1995].

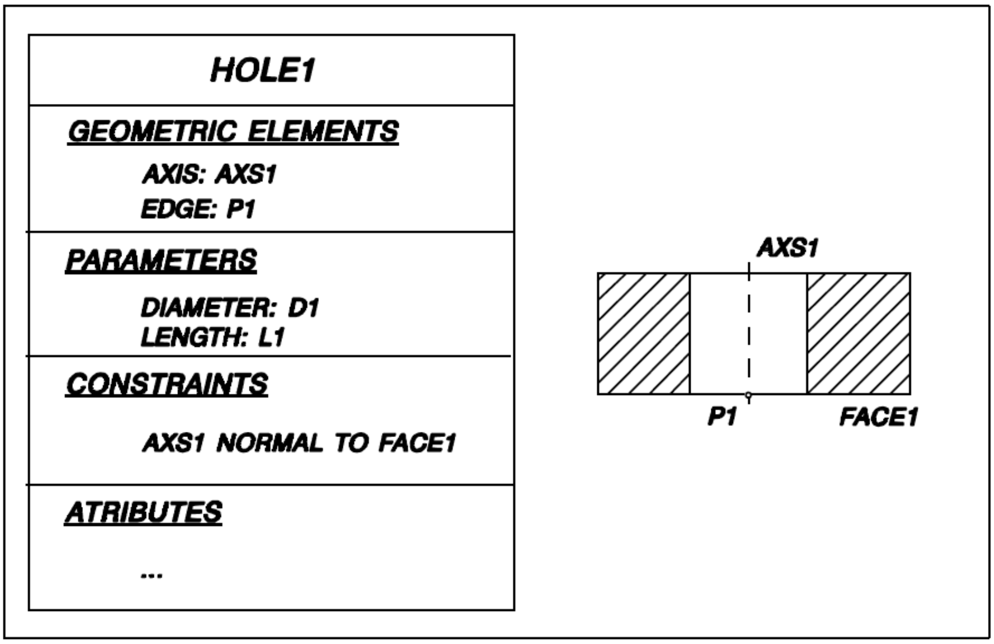


Figure 14: Example Basic feature [AIT, 1995]

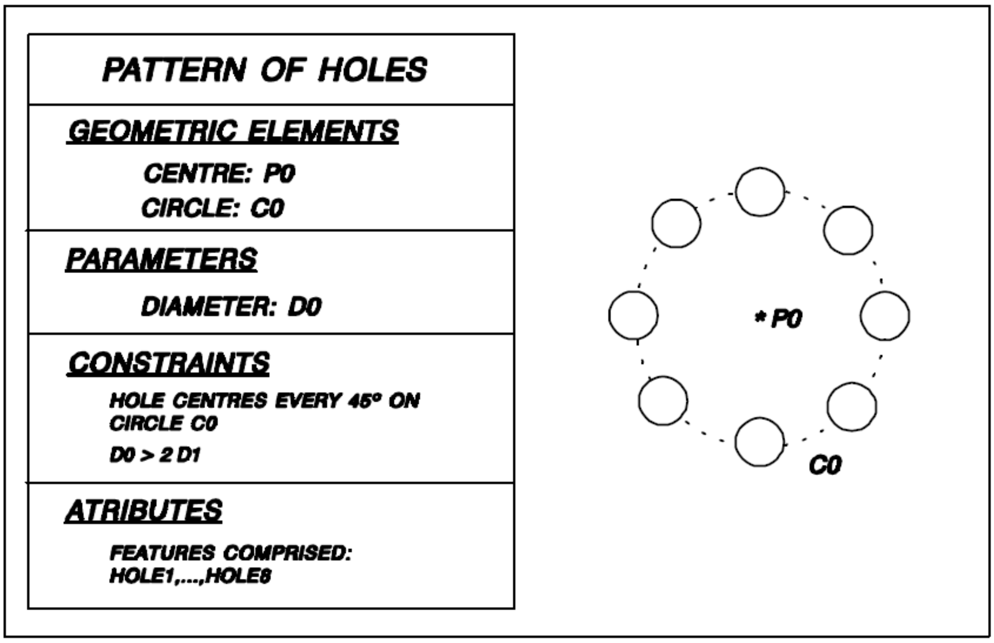


Figure 15: Example compound feature [AIT, 1995]

These two types of features enable the definition of the information structure of a part. However it is also necessary to establish relations between different parts in the form of the constraints these parts must comply with to warrant fixing [AIT, 1995]. Therefore, a third type of features, the Assembly feature, is required to contain these constraints as well as all the information concerning the union, for example its type (bonded, welded, riveted, etc.), material employed, etc. As the constraints are defined between specific constituents of the parts, and each of these is contained in a different CAD model, assembly features contain constraints between features belonging to different CAD models. Assembly features can be defined between parts of the same assembly or parts of different assemblies [AIT, 1995].

3.6 Conclusion

This chapter demonstrated the different aspects of parametric design techniques. It was possible to show that parametric design is related to many different facets and techniques. From the designers perspective it is quite difficult to distinguish between all these techniques and approaches. Furthermore it is quite important that designers get an introduction about the meaning of parametric design. The observation of the researcher during the time of this dissertation was that many designers who should learn and work with PA CAD systems have a lack of understanding what “parametric” design really means and what kind of possibilities the designers have during the design process with PA CAD systems.

The next Chapter will define the research methodology aspects important for the accomplishment of this scientific works.

4 Literature survey and definition of general PA methods

This chapter of the work will describe the important methods which are defined in the product development process and will give a definition of the terms “method” and “methodology”. The following chapter also explains the importance of methodological working during the design process. Afterwards the author also explains different research publications relevant for this research. One of the fundamentals of developing high standards and good quality products are well defined technical solutions based on design knowledge and design methods. The challenge is the connection between engineering knowledge and efficient design methods. The history of design method development is very long and therefore there are many relevant research papers in this area. Some of these conventional and general design methods are described by Hansen, 1966; Roth, 1979; Ehrlenspiel, 1974; Hubka, 1976; Rodenacker, 1976; Pahl and Beitz, 1977; Koller, 1985; VDI 2222 and Suh, 1985. This section of the work will only refer to methods described in Pahl/Beitz and VDI 2221/2222, because these works are possibly the most important works in method development. Furthermore, the important characteristics of these two methods will be described.

4.1 Definition of Method

According to the Oxford English dictionary “method” is defined as [OXFORD DICTIONARY, 2000]:

a) “A means or manner of procedure, especially a regular and systematic way of accomplishing something”

b) “Orderly arrangement of parts or steps to accomplish an end: random efforts that lack method.”

c) *“The procedures and techniques characteristic of a particular discipline or field of knowledge”*

Pahl and Beitz [PAHL/BEITZ, 1996] defined the term “method” in design engineering as analysing the structure of technical systems and their relationships with the environment. Furthermore, the aims of methods are to derive principles for the development of these systems from the system elements and their relationships [PAHL/BEITZ, 1996]. They also used the term “methodology” and defined it as a “concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology and from practical experience in different domains”. This contains the planning of actions to connect working steps and design phases according to content and organisations. Pahl and Beitz [PAHL/BEITZ, 1996] describes “method” in engineering as a “systematic proceeding aimed at reaching a certain target”. Furthermore, Feldhusen defines “methodology” as a “systematic proceeding comprising several methods and aids aimed at reaching a certain target”. Lindemann [LINDEMANN, 2007] defines method as “description of a procedure based on rules, plans which have the target of achieving a goal”. Pahl and Beitz [PAHL/BEITZ, 1996] described the following requirements for methods in design engineering:

- Methods must be easily taught and learned.
- Methods must not rely on finding solutions by chance.
- Methods must be compatible with the concept.
- Methods must encourage a problem-directed approach.
- Methods must foster inventiveness and understanding.

The above mentioned requirements are important for the development and application of methods. The reason therefore is that these requirements consider the different aspects which are necessary for a successful integration and understanding of methods in a design environment. Therefore the author will research these aspects by the application of tests, experiments and questionnaires in future work.

4.2 Design method according to Pahl and Beitz

Pahl and Beitz [PAHL/BEITZ, 1996] divide the process of finding design solutions into different working stages. Furthermore, every working stage of the design process can be regarded as a transmission of activity which is related to each other and in which information elements have a strict relationship to each other. The results of these working stages provide and deliver the input of information for the subsequent working stage and processes. Furthermore these working stages are characterized by indirect activities such as discussing, classifying and preparing [PAHL/BEITZ, 1996]. Every working stage delivers the inputs of information for the next stage. Figure 16 shows the different stages of the design method according to Pahl and Beitz:

a) Product planning and clarifying the task

b) Conceptual design

c) Embodiment design

d) Detail design

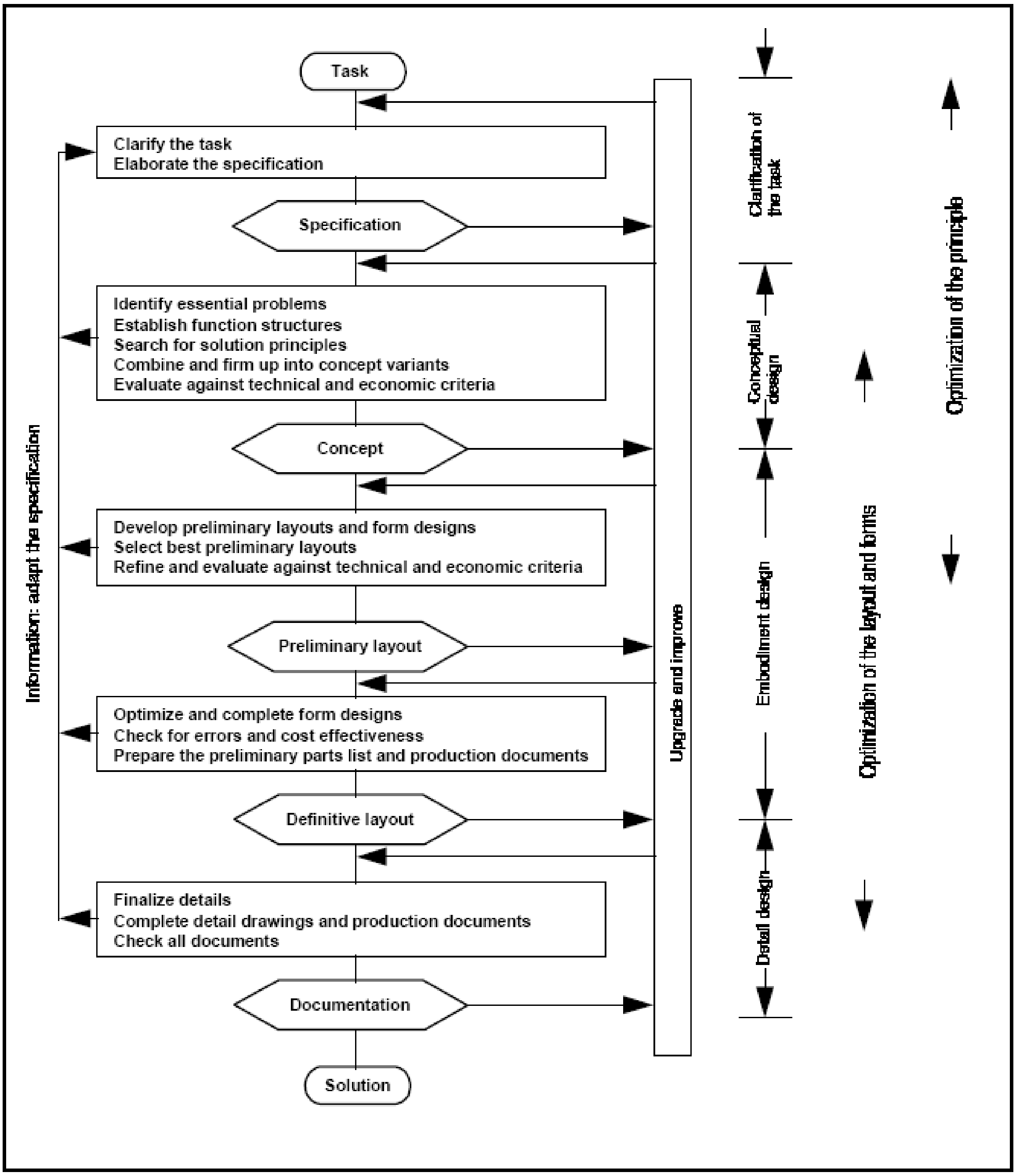


Figure 16: Process and the phases according to Pahl and Beitz [PAHL/BEITZ, 1996]

<u>*a) Product planning and clarifying the task:*</u>

This phase involves product planning, analysis of the market situation and product proposal. All market and customer needs for product development are clarified. Moreover, in this phase all product ideas and solutions will be defined and formulated in the product proposal. The result of all these tasks is the elaboration of a "requirement list"

[PAHL/BEITZ, 1996]. The conceptual design phase and subsequent phase should be based on this document that has to be updated continuously. The result of this phase is the specification of information.

b) Conceptual Design:

This design phase involves finding all essential problems, creating functional structures, searching working fundamentals and combining the functional structure with the working principles. In this phase the essential problems, function structures and working principles are defined. This step leads to the "specification of principle".

c) Embodiment Design:

During this phase designers elaborate their 3D CAD concepts (working structure, principles, solution), determine the construction structure of a technical system in line with technical and economical criteria. The results of this step are the creation of a specification of layout. Furthermore in this level there is detailed information about the product. The evolution of different variants of a product may lead to the selection of one that looks particularly promising to be the best solution.

d) Detail Design:

In this phase the arrangement, forms, dimensions and surface properties of the individual parts are laid down, and all the specifications like materials, production possibilities, cost estimation and other important points are clarified. The results of these tasks are the production specification.

Evaluation of the method:

The method according to Pahl/Beitz [PAHL/BEITZ, 1996] describes a general view of product development process in engineering design. The design phases and steps which are defined in this method are the first fundamental descriptions of the product development process. Moreover this method will still remain valid in product development process and presents important basic knowledge in design process. However, this method is not fully transferable to PA design systems. The reason therefore is that the approach according to Pahl/Beitz considers the product development process from a general view. Related to PA design there are further aspects necessary which are for example the identification, determination and modification of different kinds of design parameters (i.e. product and process parameters). Furthermore methods are necessary which help to elaborate the before mentioned parameters.

4.3 Design method according to VDI 2221/2222

In 1973 the guideline VDI 2222 (Design engineering methods of industrial products) was set up on the proposal of Kesselring and Hansen by the VDI (Association of German Engineers) and a design committee of German professors. The leader and chairman of this group which included other German professors like Beitz, Koller, Kollmann, Pahl, Rodenacker and Roth was Mr. Fritz Kesselring (Figure 17).

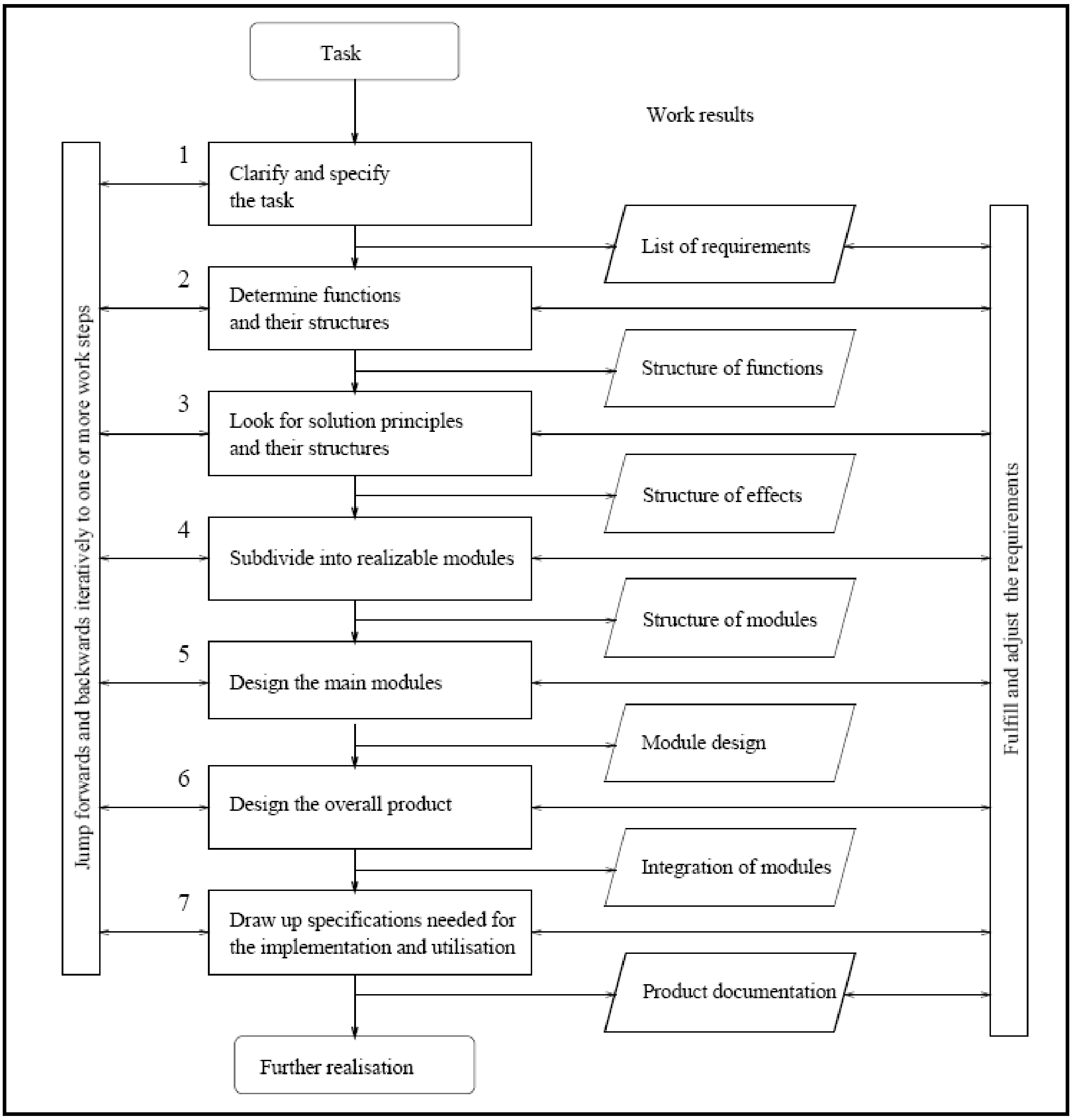


Figure 17: Method according to VDI 2221

The main objective of this committee was to develop a guideline for the development of technical products. The goal of the guideline was to propose a general methodology for designing technical systems and products and to support a methodological and systematic designing, in order to produce a more efficient working style. The guideline is independent of the engineering discipline and includes content and organizational aspects of designing. It stresses the broad application within mechanical engineering, precision mechanics, electrical equipment and software development and the planning of process engineering [PAHL et al, 2003]. The guideline encompasses the four main design phases: clarification of the task, conceptual design, embodiment design and detail design. The guideline is based on system engineering and problem solving. The design method of VDI 2222 includes four main steps:

a) Planning
b) Conceptual design
c) Creation
d) Elaboration

a) Planning:

The phase 'product planning' includes systemically searching for product solutions and new product ideas. This includes new product innovations and ideas which are essential for a successful company. Furthermore it is important to create products which fulfil technical requirements as well as economical. It is also very essential to recognise market potentials and customer needs. These results are available after doing market and customers surveys. The result of the planning phase will be the definition of a "product characteristic document".

b) Conceptual design:

The next step is the definition of the conceptual design. In the automotive industry the content of a product concept list can be for example vehicle design description, engine type, performance, torque and number of passengers etc. The results of the conceptual design contain the basic description and characteristics of the product. Afterwards there is an analysis phase of all tasks and steps. The result of this phase is for instance the technical solution of the product. Furthermore these solutions are defined by different functions. Every technical solution can be described as a kind of "Black box" system which contains design information inputs and outputs. Black box solutions are very abstract therefore it will be necessary to classify this abstract system in sub systems and sub functions.

c) Creation

This stage includes the creation of the sketches and concepts which are defined in the "conceptual" stage. Furthermore it is characterized by deeper detailing of the product design and model. The principle structures get divided into realizable modules which can be created. The product models get dimensioned and the principal functions get optimized.

d) Elaboration:

In the elaboration phase the final product documentation and the geometry (model) of the product are fully described. The functional, manufacturing and economical aspects of the product can be explored and calculated. Figure 17 shows the different phases of the methodology according to VDI 2221/2222. The biggest advantage of the method according to VDI 2221/2222 is the availability of a very simple execution procedure. Very experienced designers carry out these steps more intuitively but for inexperienced designers the steps of the described method will help to design products in a clear and comprehensible way. The results of the method phases and steps are a clear description of the design problem by means of a requirement list.

Evaluation of the method:

The method according to VDI2221/2222 describes a general view of the product development process and is therefore not transferable to PA design systems. The reason therefore is that the phases which are described in VDI2221/2222 cannot be converted to the PA design. Furthermore the design of PA parts and components require some methods of how to demonstrate the different kinds of parameters which are necessary during the virtual design process. In addition it is also required to identify and determine the product and process parameters with their relationships to each other. Therefore the general methods and approaches are not able to give solution approaches for PA design process. The design phases and steps which are defined in this method will remain valid in the product development process and presents the basic consolidated view of method development in the design process.

4.4 PA design related literature

In search of literature about methods and approaches of PA design systems it is very important to distinguish between research papers, theses and commercial books. Commercial books describe only the functionality of different parametric systems, for instance Pro/Engineer or Unigraphics [ZIEHTEN, 2006, BRILL, 2006]. Most of these books do not describe a general methodology for use during the work with PA design systems and define only specific applications of such systems. They can only be seen as a description of how to use certain functionalities offered by different CAD systems. Furthermore, for many designers, it is difficult to reflect the described approaches for their daily design works. The scientific works related to PA CAD modelling are multifaceted. All of these different works consider parametric design from different views and aspects. In the following section of this work the author will consider and review all relevant and important works related to PA design. In the next step the works (Mendgen, 1998; Schenke, 2001; Forsen, 2003) which are strongly engaged in method development and approaches with PA design systems will be considered in detail.

Vajna [VAJNA, 1998] analysed existing parametric modules and functions for the development of general remarks of parameterization in the product development process. This includes amongst others the creation of part families and the identification of form elements inside part families. Furthermore he recommended to define a relation structure of the existing constraints and to build a documentation of the parametric CAD model. But the approach according to Vajna does not consider the methodological aspects which are necessary to work with parametric CAD systems in the product development process. The reason therefore is that the focus of Vajnas work was to offer approaches for current functions which are available in commercial CAD systems like ProEngineer. Gausemeier [GAUSEMEIER, 1994] presents an application tool to define the semantics of parametric design elements. He also identified that it is very important to work with guidelines which describes the rules of working with parametric CAD models. For example how to deal with constraints of the created CAD models. The approach according to Grabowski [GRABOWSKI, 1996] includes the creation of flexible parametric design elements at an assembly level. That means the focus of his work is to structure the relations between the different design dimensions especially in constraint modelling. The structural relationship describes the geometrical constraints like planar, parallelism and coincidence between the geometrical elements. It does not consider the fixed associative relationships between the geometrical entities. In this case the methodological aspect of PA design is also not considered. That means that there is not definition of a certain methodologies of how the relevant parameters can be identified and determined. Furthermore it is not explained how the structure of the created PA CAD models should be presented to find the relevant parameters information.

Further works which are also engaged in parametric CAD modelling consider the functional aspect of CAD modelling. For example Suhm [SUHM, 1993], Heidrich [HEIDRICH, 1990], Rude [RUDE, 1991] and Benz [BENZ, 1990] developed approaches which include only the adoption of functional aspects to parametric CAD models. These approaches do not consider the methodological aspect of parametric CAD modelling. Krause [KRAUSE, 1997] developed an approach to exchange parametric information based on implicit feature-oriented product description. The focus of this work is to create architectures of how to exchange parametric elements which are used to describe parametric models. By means of such architectures the exchange of geometrical information between different parametric CAD systems can be enabled. The base of this approach is a neutral data format. Furthermore there is a generic description and representation of the parametric CAD models available. The approach according to Krause also does not consider the methodological aspect of parametric CAD modelling.

Further works which are related to integration of calculation and FEM process in design process are written by Löffel [LÖFFEL, 1997], Bachschuster [BACHSCHUSTER, 1997] and Dyla [DYLA, 2002]. The target of these methods is to create an interface between the available FEM tools (i.e. ANSYS, FLUENT etc.) and parametric CAD models. Most of these approaches are based on neutral data formats like STEP, VDAFS, DXF or XML languages. The disadvantage of the presented approaches are that there is an break (no link to the original CAD date) between the native parametric CAD models and the FEM models therefore the focus of these works is the transformation of CAD information data from certain CAD systems to the FEM tools. Modern PA systems like Pro/Engineer and CATIA V5 offer integrated FEM tools which enable a direct association and connection of native CAD data with FEM models. Therefore in case of geometrical changes the related FEM models can be updated automatically. Furthermore it is important that the developed methods are able to provide a solution of how to generate such associative relationships and how it is possible to offer further required geometrical information to downstream processes. Ledermann [LEDERMANN, 2007] presented a method to connect parametric

CAD models in the aerospace industry to FEM models. The target of Ledermann´s approach is calculating and assessing different parts of a given airplane structure in an automated way by means of a PA part library [LEDERMANN, 2007]. Furthermore aeroelastic optimization can be performed by using this library to couple the CFD Software FLUENT with the CSM code MSC.Nastran. But in this case a certain method of how to use parametric systems is not given. Radke [RADKE, 1995] developed a concept which considers manufacturing process related aspects of parametric modelling. That means how is it possible to integrate process requirements to parametric CAD modelling. Weck [WECK, 1998] developed an approach of how to connect technical product requirements like quality data with parametric CAD models. Furthermore the target of his work is the early identification of problems between technical product requirements and the current parametric CAD models. Ma and Tong [MA, TONG, 2003] used associative features to design parts of a plastic injection mould. The target of their work was to use associative features to design a cooling channel based on a fully parametric CAD model. As a result they developed a tool which is able to generate cooling channels fully automatically. In this case the methodological aspect of parametric CAD modelling is again missing. Bossmann [BOSSMANN, 2007] developed an approach to connect feature based product and process (manufacturing data) models in product development process. The work according to Bossmann is based on skeleton technology[5] and considers only the process planning aspects. Furthermore he [BOSSMANN, 2007] has analysed the product planning activities which are necessary to manufacture a parametric product. In this case the methodological aspects of how to work with PA CAD systems are not considered. The reason therefore is that the work according to Bossmann includes only the adoption of process planning to design process. Furthermore from the methodological aspect the consideration of how to represent the relationships between the process planning steps and single features is not given.

The different approaches in this section of the work which have been presented and reviewed consider only parametric design modelling from different aspects such as functional, calculation, process and product planning but not from a methodological point

[5] Skeleton technology: The skeleton technology in the context of virtual product development contains the basic geometrical entity information like points, lines, circles, solid and shapes which have the target to get a geometrical architecture of a PA design. It can also be seen as the geometrical touch point between associative parts and assemblies

of view. The next section of the following work will consider works which are strongly involved in method development with parametric, feature based and associative systems.

4.4.1 Aspects for assessment of relevant approaches

There are only a few scientific works and approaches which are engaged in method development especially of PA systems. These approaches are developed by Mendgen, Schenke and Forsen [MENDGEN, 1998; SCHENKE, 2001; FORSEN, 2003]. In order to be clear and for a better assessment of the reviewed research works the author has identified different aspects which are important during the design process using PA system and which are important for this work. These have been identified during the empirical phase of the research by means of questionnaires, tests, experiments and interviews with CAD experts and coaches (the results can be seen in chapter Four. The first aspect for consideration is recommended by Vajna [VAJNA, 1998] and in the VDI guideline 2209 [VDI 2209, 2006]:

- Preliminary consideration of parametric design process which means that the parameters which are relevant should be investigated before starting to design the PA components.
- Structural consideration of parametric design process which means that the parameters and the relevant associative relationships should be created in a structured way.
- Process related aspects during the design process with PA systems. That means that the parameters which are relevant for the downstream processes should be created in a way that the process participants are able to find this information in a better way.

The first aspect which considers the preliminary consideration of the design with PA systems contains the question of how best to design a PA model. According to Vajna [VAJNA, 1998] working with parametric systems requires accurate planning and organisation of the modelling process. This includes not only the embodiment design with certain CAD systems but also the organisational and process related aspects. Furthermore because of the complexity of parametric systems designers need to plan a “modelling strategy” for their parts and assemblies. The reason is that designers and design teams have to clarify which associative design information like geometrical entities (i.e. shapes, lines, points etc.) are required. The next aspect is related to the functional aspects of PA systems which can be subdivided into specific “parametric” and specific “associative” relations. The parameter related aspects should consider the identification and determination of the parameters and their relationship to each other. Furthermore it is important to clarify if the developed solutions provide methods to accomplish this aspect and if the required parameters can be classified in different categories (i.e. geometrical and non-geometrical). The associativity consideration includes the aspect whether the developed methods offer solutions which can be used to create associative models. That means if the approaches consider the way of how to identify and to determine the associative relationships between the geometrical entities and parts. Furthermore how is it possible to structure and prepare such associative relationships before and during the design process?

The process related aspects which are important for a continuous product development process should also be considered. That means the availability of certain parameters or geometrical information which is required and essential for a stable PA design should be ensured. In this case it is also important to clarify if the presented method considers this aspect. The organisational aspect considers points which are important to create fully associative parts and assemblies. That includes activities which are necessary to interact and provide the associative geometry between all the participants in the design process. This section of the work will now present the reviewed scientific work and papers related to PA design.

4.4.2 Approach according to Mendgen

The first approach is developed by Mendgen [MENDGEN, 1998] and is based on defined rules. These basic rules define that parametric CAD models should be a) well-defined b) simple and c) complete. The first point "well-defined" CAD models mean that designers should consider the semantics and naming of their parts and assemblies. Furthermore naming of certain features is necessary because of the importance of such features for the further design process. For example the naming of certain screw threads is necessary because the manufacturing engineer will be able to find this design information fast. The second aspect, "simple CAD models" implies that the information which is stored in parametric CAD systems should be kept simple. However the problem in this case is that the interpretation of the term 'simple' is quite difficult because every PA part or assembly can be complicated and the point of view decides if a part is complex or not. The opinion of the author is that parametric systems are very challenging for every designer and therefore this point is strongly related to the skills and CAD knowledge of the designer. The last rule defined by Mendgen [MENDGEN, 1998] describes that CAD models should be "complete" that means that changes should not lead to data information loss. This point is also not clear enough and Mendgen has not give a definite answer what he really means with "complete and robust" CAD models. Does it mean that parametric models should be able to regenerate themselves during the geometrical changes or does it means that the system should not lose information? Not all of the basic rules which are defined by Mendgen [MENDGEN, 1998] can be fully understand. The aspect of "well defined" CAD models can be accepted and is important during the work with PA system because the identification of different parts, assemblies and geometrical entities can be considered. Mendgen divides the parametric design process into six phases which include [MENDGEN, 1998]:

- Building the modelling elements and their constraints to each other. In this case the constraints (i.e. coincidence, parallelism, planar) between the geometrical parts and assemblies should be defined. This aspect does not consider the fixed associative relationships between the geometrical parts and assemblies.
- Structuring in single components. In this step components can be divided into different modelling features. In later product development stages the modelling features can be joined in one component. This approach can be used in creating different features by means of Boolean operations.

- Coupling and uncoupling. According to Mendgen this step is important for constraint based modelling because this step is necessary to work out the constraints between the features. For instance there is a parent and child relationship between a plane and the created body or the geometrical entities.
- Changes. According to Mendgen in this step it is important to think about possible changes to CAD models, so designers are able to create dynamic and flexible CAD models.
- Clean modelling: In this step it is very essential to name all parts and features and so it will be easy to find the created components. This aspect considers only the identification of part properties and attributes. Mendgen developed an assistance tool for parametric CAD systems based on TCL (Tool Command Language) language which is called “constraint control”.

The main focus of the approach according to Mendgen is the application of a method in geometrical constraint design (parallelism, tangency, coincidence etc.) without any associative relationships to the design context (fix connection to the surrounding geometry) and environment [MENDGEN, 1998]. Furthermore the method developed by Mendgen is based on VDI 2221. But he developed an assistance system (constraint control) which supports designers to apply the method according to VDI 2221 in relation to PA systems. One of the aspects which are not considered by Mendgen’s approach is that there is no logical relationship between the stages which are defined in the developed system “constraint control”. Normally a method should guide designers to apply steps to achieve their goals faster but in this case a methodical procedure is not recognizable. For evaluation of the approach according to Mendgen as already mentioned in the section before there are aspects which are important to be considered during the design process with parametric systems. The aspect concerning preliminary consideration of relevant parameters and associative relationships is only partially considered by Mendgen. That means his approach [MENDGEN, 1998] recommended thinking about possible changes which can be made to a CAD model. However from the author’s point of view for the designer it is important to have at first an overview about different parameters which describe the geometrical CAD model. Moreover it is important to work out the details of important parameters which can be changed. Therefore before starting to create CAD models it is important to identify and determine the different kinds of parameters which are available in CAD models. Then the designer is able to think about possible changes to a particular CAD model. Related to associative design, Mendgens [MENDGEN, 1998] work does not consider this aspect. That means there is not a method of preliminary consideration to identify and determine associative relationships. Mendgen [MENDGEN, 1998] described only a method of how to create geometrical constraints (parallelism, coincidence, etc.) and developed therefore the tool “constraints control”. From the functional aspect of parametric design which includes “parametric” and “associative” design information Mendgen does not consider a certain method to represent the available parameters and associative geometrical elements. Furthermore the relationships between the parameters and associative geometrical entities which are important during the creation of a complex CAD part and assembly are not considered. The structural consideration aspect of PA design which includes a transparency and clear modelling process is only partially considered by Mendgen. He defined only very rough statements like *“structuring in single components and dividing in different modelling features”*. But the structural aspects in the design process have to consider the important design information inputs (i.e. design environment and product requirements) which are the basis of the parametric design and also design outputs which have to be delivered by designer for the downstream process. Therefore the structural aspect of the PA design process should be able to organize the required information in consideration of the above mentioned aspects. The process related aspects which include downstream processes like FEM and CAM are not considered by Mendgen. In the case of integrated PA CAD modelling and because of the fixed creation of associative relationships between design and FEM or CAM processes a method is necessary which considers the process related aspects for example how to structure the associative geometrical information in down-stream processes. Therefore the newly developed integrated method of PA design in the present research should consider this aspect. The final important aspect which is related to the organisational aspect considers as aforementioned the activities which are necessary to interact and provide the associative geometry between all the participants in the design process. This aspect is not considered by Mendgen. The reviewed work of Mendgen shows that specially related to PA design an integrated approach is not fully considered and presented. But the work of Mendgen defines some usable basic rules which should be considered during parametric design.

4.4.3 Approach according to Schenke

Further research related to the parametric design method is defined by Schenke [SCHENKE, 2001]. The main target of his work is to identify the different kinds of parameters which are available during the different stages of the product development process. The approach of Schenke does not define a “new” method of parametric design but uses only the existing method according to VDI 2222 (planning, concept design, creation, elaboration). It only describes which kinds of parameters exist during the whole product development process. According to Schenke [SCHENKE, 2001] parameters which are used during the product development process include a level of uncertainty and the design information varies over the whole design process (Figure 18).

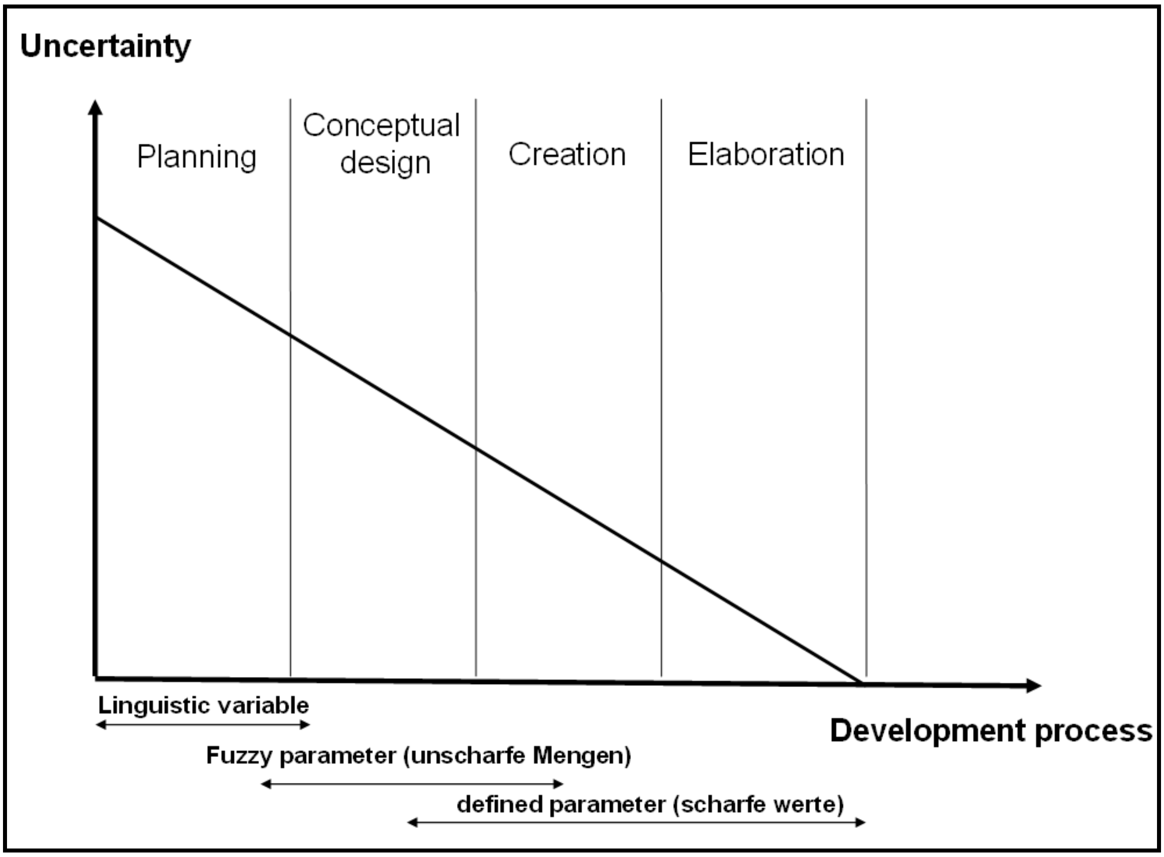


Figure 18: Different kinds of parameters [SCHENKE, 2001]

At the early stage of product development, parameters are not well defined and Schenke describes this kind of parameter as “unscharfe” (the term “unscharf” is German and means fuzzy, unclear or cloudy) [SCHENKE, 2001]. Furthermore, in later product development phases the parameter (information content) gets more clear and detailed. Schenke describes these parameters as “scharfe” (the term “scharf” is German and means clear or well defined). Schenke also identified that in general there are the following kinds of uncertainties: [SCHENKE, 2001] (a) incompleteness of information which means input data are not available; (b) impreciseness of information which means that the content of certain information is not complete; (c) unreliability of information which means that the required information might not be available; (d) inconsistency of information which means that information are contradictory. Furthermore there are also four kinds of uncertainties related to parametric design [SCHENKE, 2001], these are: data-, linguistic-, relation- and inconsistency-uncertainties. For solving and classifying “unscharfe” parameters in the early stages of product development Schenke used fuzzy set theory and developed the assistance system “PARAKON” (PARAmetrische KONstruktion), in English ‘parametric design’.

The system “PARAKON” is based on four different modules. One module is created for the design decision process which contains all relevant decisions related to part or assembly (product) [SCHENKE, 2001]. It contains also the properties of the parts and assemblies like part name or part number. The second module contains a procedure and description editor to create parts and assembly. The third module includes modelling arguments which include what kinds of tasks are necessary to create the parts and assemblies. The final module is the method archive which contains all steps of component creation. The “PARAKON” tool developed by Schenke does not define a method of how to work with parametric systems. It is only a tool to collect unconnected information during the geometry creation. One of the important points which is not considered by the defined procedure of Schenke is that this approach cannot be seen as a new “method” because firstly it uses an existing method (VDI 2222) and secondly the main part of the work contains the solution approach of how to deal with the uncertainty of the parameters during the design process. For evaluation of the approach according to Schenke as already mentioned in the section before there are aspects which are important to be considered during the design process with parametric systems.

The aspect “preliminary consideration of PA design process” is mentioned by Schenke but the methodological approach of how to accomplish this process is not defined. As aforementioned the focus of Schenke’s approach is to solve the problem of parameter certainty and uncertainty in early stage of product development. That means the approach give some solutions of how to calculate the aspect of uncertainty during the creation of different kinds of parameters. But Schenke also states that there are hierarchical dependencies between some parameters. This aspect is a very important one because the more important and relevant parameters can derive the other parameters. From the functional consideration aspect of parametric design which includes “parametric” and “associative” design information Schenke offer some good solutions approaches related to skeleton models and how to create such models. Furthermore the relationships between the parameters and associative geometrical entities which are important during the creation of a complex CAD part and assembly should be structured in a clear way. But the structural consideration aspect of PA design which includes a transparent modelling process is partially considered by Schenke.

The approach according to Schenke considers that a product can be divided into assemblies, subassemblies and components. But the structural aspects should consider the important design information inputs and outputs. Therefore the structural aspect of the PA design should be able to structure the required information in consideration of the above mentioned aspects. The process related aspects which include downstream processes like FEM and CAM are not considered by Schenke and in case of integrated PA modelling there is a method necessary which considers the process related aspects for example how to structure the associative geometrical information for down-stream processes. The last important aspect which is related to the organisational aspect considers as aforementioned the activities which are necessary to interact and provide the associative geometry between all the participants in the design process. In general the approach according to Schenke does not offer an integrated method for PA CAD modelling.

4.4.4 Approach according to Forsen

The next relevant work is by Forsen [FORSEN, 2003]. It presents the parametric design approach “PAKO” (PAKO is the German term for PArametrische KOnstruktion, in English parametric design). The focus of Forsen’s [FORSEN, 2003] approach is to transform the parametric design to a technical system and to describe the properties of this technical system. One of the aspects which have been pointed out by Forsen [FORSEN, 2003] is that the working process with PA design systems requires a certain “thinking process” and therefore the modelling process should be planned. The PAKO approach contains three different phases which are subdivided into six steps. The phases are pre-CAD phase I, pre-CAD phase II and the CAD modelling phase itself. The subdivided steps are 1) separation of the system PAKO from the design environment, 2) formation of the system PAKO, 3) Formation of the system structure of PAKO, 4) Formation of the system hierarchy, 5) Formulation of the design strategy and 6) Formation of the system from concept to detail. Furthermore the “PAKO” system according to Forsen is based on 25 different definitions which describe the relationship between the “PAKO” system itself and his environment. According to Forsen the most important definitions related to PAKO are:

Definition 3: System PAKO:

The PAKO system contains many CAD elements which have attributes and relations between each other.

Definition 4: Subsystem PAKO:

Every element of the PAKO system can be a sub-element of another system.

Definition 5: CAD elements of the system PAKO:

CAD elements can be seen as the origin of the defined system.

Definition 6: Relation of the PAKO system:

The relations between the PAKO systems are important. These relations can be created as a result of history-based or associative design.

Definition 7: Relation structures of the system PAKO:

The system PAKO is the result of the relations between the CAD elements.

Definition 8: Structure of the PAKO system:

The system PAKO contains variable structures which can be geometrical or associative.

Definition 9: Feedback of the PAKO system:

PAKO system considers feedback neither direct nor indirect.

Definition 10: Environment of the system PAKO:

PAKO exists in a design environment and this environment impacts and influences the PAKO system.

The above described definitions show that the approach developed by Forsen considers the parametric design process from the system design aspects. Therefore the transformation of the method to a real and practical design process is quite difficult. The method according to Forsen can only be seen as a very abstract workflow of system design. Furthermore there is not any consideration of parametric design because as aforementioned this approach describes only the specific characteristics of the PAKO system. That means that the method according to Forsen does not answer the question how to work with a parametric system and how is it possible to identify the relevant and important parameters during the design process. Further open questions are:

- Which important parameters are required to create PA CAD models?
- How can the relationship between the parameters be identified and created?
- Which kinds of preparations are necessary to identify important parameters and their relationships to each other?
- Which kind of parameters exists in the CAD model?
- What kind of associative relationships exists?
- How is it possible to structure the required design information inputs and outputs?

The preliminary consideration aspect of the PA design process is partially considered by Forsen. That means his approach [FORSEN, 2003] recommended to analyse the environment of the PAKO system and to identify possible relationships. But the preliminary consideration of how to identify and determine important parameters is missing. Moreover it is important to work out the details of important parameters which can be created. From functional consideration aspect of parametric design which includes "parametric" and "associative" design information Forsen does not define a method to represent the available parameters and associative geometrical elements. Furthermore the relationships between the parameters which are important during the creation of a complex CAD part and assembly are not considered. The structural consideration aspect of PA design which includes a transparent and clear modelling process is partially considered by Forsen. It describes only that the PAKO system contains assembly and subassemblies. But the structural aspect contains the arrangement of design information inputs and outputs which are the basis of parametric design. The last aspect which is related to the organisational aspects considers as aforementioned the activities which are necessary to interact and provide the associative geometry between all the participants in the design process. This aspect is not considered by Forsen. The work of Forsen defines only some theoretical view of PA design and defines basic rules which are related to his PAKO system. The approach according to Forsen considers only that there is a transformation of system theory to parametric design and the adoption of the rules which are valid in technical system engineering has been borrowed, transformed and used for parametric design systems. For that reason this approach can be seen as a very theoretical consideration of parametric design and it cannot be used in real design environment. The reason therefore is that in real design environment there are different design requirements. Designers for example distinguish between different design levels like part and assembly design or different process levels like concept and detailed design. But the approach according to Forsen does not consider all this important aspects. Furthermore for a designer it is also difficult to transform the design task (creating a PA CAD part or assembly) in an abstract technical system through the whole design process.

Table 3 below shows the significant properties of the different works:

	Mendgen	Schenke	Forsen	Salehi
Aspect 1: CAD system independent aspects				
Consideration of preparation phase of design and modelling process	○ **(partly considered)**	- **(not considered)**	● **(fully considered)**	● **(fully considered)**
Aspect 2: Functional aspects				
Aspect 2.1: Parameters:				
Identification of different kind of parameters geometrical = i.e. values and non geometrical = i.e. weight, material)	○	●	-	●
Identification and determination of different parameters	○	-	-	●
Identification of the relationship between the parameters	-	●	-	●
Aspect 2.2:Associativity:				
Consideration and identification of different kinds of associativity (unidirectional and bidirectional).	○	-	○	●
Identification and determination of different kinds of associative relationships. (i.e. between parts and features)	-	-	○	●
Aspect 2.3: Constraints				
Consideration of constraints between parts and assembly features	●	●	-	○
Aspect 3: Structural aspects of CAD modelling				
Identification of structural design inputs and outputs	○	○	○	●
Determination and classification design information	-	-	-	●
Aspect 4: Process related aspects				
Consideration of downstream processes like CAE and CAM	-	-	-	●

Table 3: Comparison of the different methods by means of different aspects

4.4.5 Literature related to Adapter and Multi-Model-Technology

Beside these three scientific works which have been explained in detailed there are also papers which refer to PA design. This section of the thesis will consider these papers. Further work related to PA systems has the problem that the developed approaches define only solutions which are often component oriented and the transformation to other applications is often difficult. That means that the developed methods only offer solution approaches for the parametric design of certain components (for example crank shaft). The problem of some papers is that from the scientific view there are some gaps of “term” definitions which have been used in such papers and therefore it is quite difficult to assess the papers and understand the intents of the author. Papers and works which are related to PA design use both, “adapter” and “Multi-Model-Technology” which allow the creation of linkages between geometrical entities and objects. These technologies do not present a certain “method” or “methodology” of how to design a PA part or assembly but show the possible connection technique between the geometrical entities and objects. Furthermore the reviewed papers primarily describe techniques of how to structure the PA assemblies in relation of using adapter or multi model technique. For a better understanding of these techniques the author will describe in this section shortly the characteristics of adapter and multi model creation.

The adapter technology in the context of virtual product development contains the basic geometrical entity information like points, lines, circles, solid and shapes which have the target to get a geometrical architecture of a PA design. It can also be seen as the geometrical touch point between associative parts and assemblies. By means of adapter modelling the specific basic geometry and driven parameters can be controlled separately. The characteristic of adapter parts and assemblies are [HASLAUER, 2005]:

- Adapter models contain geometrical entities and parameters i.e. points, lines, shapes and solids.
- Adapter models are characterized by an exactly defined geometrical interface
- Adapter models use linear associative relations.
- Adapter models are hierarchically ordered.
- Adapter models can be defined by simultaneous or concurrent engineering teams.
- Adapters can also be considered as an interface to the downstream processes (CAM, CAE).

Multi-Model-Technology is a product modelling approach that joins object-oriented technology with feature-based modelling technology. It uses object-oriented technology to generate the object-model of a product and process-oriented feature-based modelling technology to build the model of an object [XU, 2002]. Furthermore Xu and Wang define that the object-model of a product describes the "static" structure of the product and for most of the time this structure is relatively stable. Every object represents a complete and detailed model in the product development process, thus it is called a Multi-Model structure. Xu and Wang also recommended that the Multi-Model-Structure must be created by all members of the team which are involved in the PA design process and should be planned carefully. This aspect is a very important one because for creating such multi model structures and associative relationships it must be clarified which geometrical information is required by other designers, design teams and process partners. Therefore Xu and Wang mentioned that there are new methods and approaches necessary to handle this situation. The defined Multi-Model Structure according to Xu and Wang contains the description of a four layer system which is stored in one CAD part which is based on different solid models. The first layer contains the elements and basic geometries and the second layer contains the function. The third layer is a rough part model layer which consists of rough part model and the drafting model. The fourth layer is the finished part model and its drawing. It is the result of the rough part model subtracted from the machining model. By means of that Multi-Model-Technology, Xu have designed a cylinder head. The Multi-Model-Technology represents the creation phase of the geometry in embodiment design with a PA system but the important methodological question of how to define and determine such geometrical information is not answered. Furthermore it is not clear how to get certain geometrical information which is necessary to build such Multi-Model Structures.

Another paper related to PA design is written by Avallone et al at FIAT Automotive [AVALLONE et al, 2001]. They present a procedure on how to create adapter models with PA systems in Body in White development. Their structured steps are quite similar to the approach according to Forsen. They also mentioned that the design elements should be designed from concept to detail level. Furthermore the design steps are divided in three stages which are stored in different files: a) the first file gives only a set of surfaces and construction features; b) the second file uses these features to build a primary model; and c) the third file allows the complete part to be obtained. The idea to structure the information in different filed should help to reduce the level of components complexity. It is not a method of how to create PA models but the structuring aspect of the created components can be evaluated as very positive. Furthermore by means of the suggested approach it is possible to handle the created PA parts and assemblies in a better way from data management aspects.

Wang and Levi defined a structuring layout for using parametric systems in vehicle design [WANG, LEVI, 2005]. This structuring layout presents a top-down-modelling approach; to start with a parametric 3D adapter model characterizes the vehicle architecture, followed by a set of 2D-sections that explain the vehicle size and the shapes of the components, then the beams that are the load carrying members of a vehicle (connecting surfaces for the beams). It can be further decomposed into components. Wang and Levi described a structure layout of a parametric vehicle model and they described their adapter model as a skeleton model. According to them [WANG, LEVI, 2005] a parametric skeleton *"is composed of a series of 3D control points connected through 3D curves in the space. It is designed to capture the topology of vehicle architecture. The control points represent the hard points of a vehicle, which include the parametric section positions and orientations, and the surface intersection locations, also known as joint locations. The 3D curves passing through these control points represent: 1) centre line of the pillar surfaces; 2) opening lines, such as door opening lines, windshield and backlight opening lines; 3) contour or profile curves on panel surfaces, such as roof panel and quarter panel"* (Figure 19).

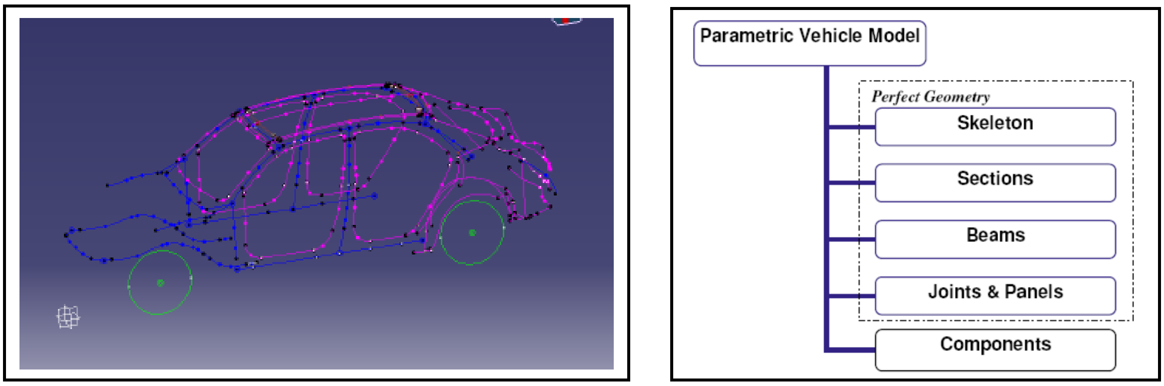


Figure 19: Parametric vehicle model structure [WANG, LEVI, 2005].

Further techniques related to PA design have been developed at Daimler AG Research and Development Centre. They also use Multi-Model-Technology to design their PA parts and assemblies. Figure 20 shows the Multi-Model-Structure of a cylinder head [KATZENBACH, 2002] designed at Daimler AG. The problem in this case is that this structural approach cannot be seen as a method which describes a certain procedure on how to work with PA systems and can rather be seen as a structural support of the required information. Furthermore, Katzenbach prefers the application of different CAD-templates in parametric modelling. According to Katzenbach [KATZENBACH, BERGHOLZ, ROHLINGER, 2007] there are different kinds of templates which can be used in product development process. These templates are function, concept, study and part templates. Function templates include only basic geometrical information and are mainly applied for providing the main geometrical dimensions and specification. The use of concept templates includes main characteristics of vehicle models like sedan, convertible or SUV. The generic design information structure, independent of the level of detail, is the basis of the archiving templates [KATZENBACH, BERGHOLZ, ROHLINGER, 2007]. This structure is a summary of different information aspects of a comprehensive product description. Depending on the actual development task, the necessary information is activated and shown in the expected context.

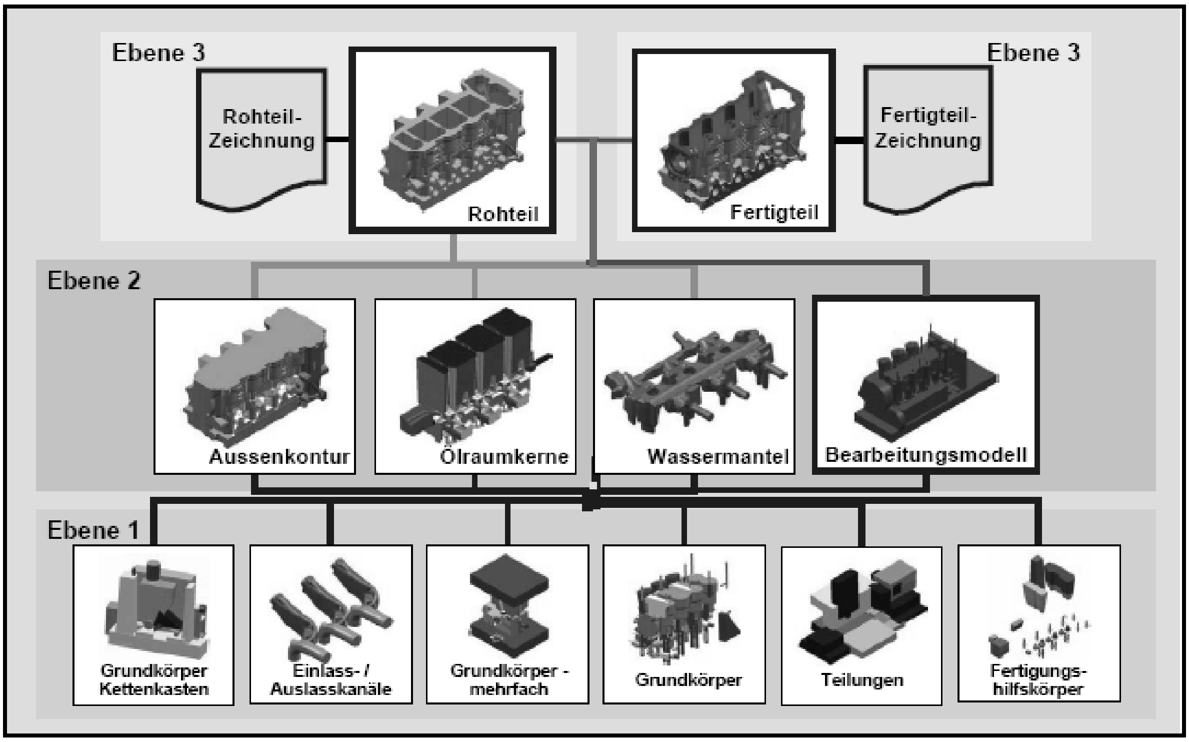


Figure 20: Multi model structure of a cylinder head [Katzenbach, 2002]

Furthermore there are many commercial books [BRILL, 2006; TALARCZYK, 2005; BRAß, 2003; HASLAUER, 2005; WEISSBACH, 2005] for different CAD systems which also describe "methods" to use different PA systems. But the focus of these commercial books is the description of the functions which are available in the related PA systems.

The usage of the term “method” in this case can rather be seen as the description of functions of such systems.

4.5 The application of PA CAD systems in automotive and aerospace industry

The idea of using PA design tools in the automotive and aerospace industries is not new. But it is quite difficult to get information about the application of such systems in the industry. The reason is that most automotive and aerospace companies are interested to keep their knowledge for themselves and this point is one of the parts of advantage in competition against other companies. Because of the industrial background of the present research, for the author it was very important to find material and papers which have also an industrial context. But in search of literature and works related to PA design in the automotive and other industry it was not very easy to get full information about the activities in different companies. Therefore the author can only reference some few documents which were available in the world-wide web (WWW) and personal contacts in the automotive industry.

In general the author was able to find some guidelines related to use PA systems in automotive and aerospace industries. It was possible to find an example of the 3D modelling rules at AIRBUS and by means of this example it becomes very clear what the content of the described methods are. These guidelines described in general only how to use certain functions in different PA system environment. Furthermore it is a description of 3D CAD system function in relation to the company’s internal product data management (PDM) system. Furthermore these “methods” focus the functional interaction between certain PA systems and the surrounding information technology.

Another task of such guidelines is to help designers to know which functions are allowed to be used and which are not. Therefore these guidelines do not describe general methodology of how to use PA systems best. Furthermore these guidelines can only be seen as a functional support for designers.

4.6 Conclusion

The different approaches which have been presented and reviewed in this section of the work consider parametric design modelling from different aspects like functional, calculation, process and product planning. But in general a complete, integrated and approach of how to work with PA CAD systems has not been presented in previous work. The results of the literature survey presented that there are four different aspects which are important during the design process with PA CAD systems. These are:

(1) A pre CAD phase which is independent from the CAD system and includes the consideration of how to prepare and understand the relevant parameters and associative relations of the CAD components which should be considered.

(2) The functional aspects of the PA design process which is divided in parameter and associative issues of the PA CAD models. That means it is quite important to be able to identify, determine and create the relationships between the parameters and associative relationships during the design process with PA CAD systems. Furthermore designers need methods to be able to identify and determine these complex relationships between the parameters and associative relationships during the design process.

(3) The structural aspect considers the identification, definition and classification of the different design information inputs and outputs during the design process. That means how is it possible to give designers approaches to be able to identify and classify such design information.

(4) The process related aspect considers the downstream related process information like CAE and CAM. That means designers needs approaches to be able to identify and determine such information with their process partners.

Figure 21 shows the relevant aspects of the literature survey related to work with PA design systems and methods.

Aspect 1: CAD system independent aspects
Consideration of preparation phase of design and modelling process
Aspect 2: Functional aspects
Aspect 2.1: Parameters:
Identification of different kind of parameters geometrical = i.e. values and non geometrical = i.e. weight, material)
Identification and determination of different parameters
Identification of the relationship between the parameters
Aspect 2.2:Associativity:
Consideration and identification of different kinds of associativity (unidirectional and bidirectional).
Identification and determination of different kinds of associative relationships. (i.e. between parts and features)
Aspect 2.3: Constraints
Consideration of constraints between parts and assembly features
Aspect 3: Structural aspects of CAD modelling
Identification of structural design inputs and outputs
Determination and classification design information
Aspect 4: Process related aspects
Consideration of downstream processes like CAE and CAM

Figure 21: Important aspects during the literature survey

Based on the results of the literature survey and the aspects which are presented in Figure 21 the author has undertaken a series of studies in an automotive industry environment, including questionnaires, interviews and studies of existing parts. The main target of this descriptive phase was to address the important points which have been identified in the literature survey. Furthermore, the Descriptive Study should help to capture the experience of the PA CAD users in an industrial context. The relevant design research methodology and the results of this descriptive phase will be presented in the next chapter.

5 Descriptive Study I

This chapter of the work presents the results of the Descriptive Study I which were based on a) questionnaire b) interviews with CAD experts and c) the investigation of already created parts and assemblies with PA CAD systems. The questionnaire in the present work is a mixture of closed-ended and open-ended questions. The goal of this questionnaire was to get more information about current knowledge of the designers and their work experience with PA CAD systems based on the findings in the literature survey. Furthermore it was important to identify if the aspects which had been identified are valid or not. The questionnaire is based on 20 different questions.

All of the respondents (there were 153 in all) are employed in the automotive industry sector. Most of them (96%) are working as designers. That means that they have regular contact with designing PA components. Furthermore in this chapter the most important issues which have been identified during the Descriptive Study I (results of the questionnaire, results of the interviews and the results of the analysis of existing PA CAD parts and assemblies) will be presented. The table shows the aspects of the literature survey which has been combined with the asked questions.

Aspect 1: CAD system independent aspects	
Consideration of preparation phase of design and modelling process	Question 6
Aspect 2: Functional aspects	
Aspect 2.1: Parameters:	
Identification of different kind of parameters	Question 11
Identification and determination of different parameters	Question 12, 13, 14
Identification of the relationship between the parameters	Question 18-
Aspect 2.2:Associativity:	
Consideration and identification of different kinds of associativity	Question 19
Identification and determination of different kinds of associative relationships.	Question 20
Aspect 2.3: Constraints	
Consideration of constraints between parts and assembly features	---
Aspect 3: Structural aspects of CAD modelling	
Identification of structural design inputs and outputs	Question 15, 16
Determination and classification design information	Question 15, 16
Aspect 4: Process related aspects	
Consideration of downstream processes like CAE and CAM	---

Table 4: Combination of the important aspects from literature survey to questionnaire

5.1 Results of the Questionnaire study

The questioning was carried in automotive company. Marshall [MARSHALL, 1988] mentioned that a response rate lower than 90% will bias the results. At response rates of less than 60% it is very difficult to interpret the results at all. To make sure that the results of the questionnaire are usable the author has implemented and carried out the questionnaires with the respondents inside a CAD workshop. The questionnaire in the present work is a mixture of closed and open questions, divided into two parts. The first part contains general questions about design activity, experience, durability, and working skills with PA CAD systems. The second part contains questions related to functional and process aspects of PA design. The questions serve to exemplify problems during the design process with PA systems and address the issues which have been identified in the literature survey. Furthermore the main goal of the questionnaire is to get a better understanding of possible challenges and problems during the work with PA systems. The design of the questionnaire is based on the Goal Question Metric (GQM) approach [BASILLI, 1988]. The GQM is a top-down approach to create a goal-driven measurement system, in which the researcher starts to define goals, poses questions to tackle the research goals, and identifies metrics that present answers to the questions [BASILLI, 1988].

The **Goals** at the top of the GQM tree are the measurement goals that are the outcome of step 1 of the GQM process. They are quantified by their linkage to questions and metrics as noted in the mapping, and include four aspects to describe what the measurement should achieve;

Object: The product or process under study; e.g. researching of PA CAD design environment in industrial context;

Purpose: Motivation behind the goal (why); e.g. better understanding of the design process with PA CAD systems and the identification of improvement potential (identification and determination of relevant parameters and associative relationships, research of the structural representation of parameters and associative design information);

Viewpoint: Perspective of the goal (who's viewpoint); e.g. CAD designer; CAD trainer;

Environment: Context or scope of the measurement program; e.g. industrial context, design department;

Questions in the GQM approach help identify interpretations of the goal that may exist among the stakeholders as well as constraints imposed by the environment. Typically, at the project level, conceptual measurement goals are identified relating to product quality, process, resources, or the environment [BASILLI, 1988].

The questions are about the identification and determination of the relevant design parameters and associative information during the design process. Finally, Metrics are about examining the questions which could be answered, moving from the qualitative to the quantitative level. Once goals are refined into a list of questions, metrics need to be defined that provide all the quantitative information to answer the questions. The questionnaire was carried out in an automotive company and the respondents were designers in power-train development. The basic conditions of the questionnaire in Descriptive Study 1 are listed in Table 5:

Environment	Automotive Industry and suppliers
Participants	153 power train designers from automotive company and suppliers
Time constraints	90 minutes for 20 questions
Team size	Groups of 10 people in different CAD design workshops
Total duration	5 Months (from creation phase to the analysis of the questionnaire)
Role of researcher	Accompanying the designers (explaining and answering questions)

Table 5: Basic conditions of the questionnaire

The goals of the questionnaire were to research a) the CAD knowledge and experience of the designers; b) the work experience of the designers; c) the understanding of the respondents related to PA CAD systems; d) the weaknesses and problems during the design process with PA CAD systems; e) the structural aspects of the design information inputs and outputs. 20 questions were created. The questions asked are presented below:

1. To which group would you assign your activities?

☐ Designer ☐ Digital Mock Up engineer

2. How many hours per week do you work (design) with CATIA V5 on average?

☐ 10 hours ☐ 20 hours ☐ 30 hours ☐ 40 hours

3. Since how many years are you working with parametric system (CATIA V5)?

☐ 1-2 years ☐ 2-4 years ☐ > 4 years

4. My expertise in the use of PA is:

☐ good ☐ very good ☐ excellent

5. The work with PA systems (CATIA V5) makes my activity as a designer considerably easier.

☐ agree fully ☐ do not agree ☐ other opinion

6. Before to start to design with PA systems (CATIA V5) I think about the construction and structure of my models.

☐ agree fully ☐ do not agree ☐ other opinion

7. At the work with PA systems (CATIA V5) I have an exactly defined approach (methodology)?

☐ agree fully ☐ do not agree ☐ other opinion

8. During the work with PA systems (CATIA V5) it is necessary to think about the modelling process.

☐ agree fully ☐ do not agree ☐ other opinion

9. I use the possibilities which are offered by PA systems (CATIA V5) very well.

☐ agree fully ☐ do not agree ☐ other opinion

10. I do not have enough time to be strongly engaged in the construction and methodology of my models?

☐ agree fully ☐ do not agree ☐ other opinion

11. During the modelling process I am able to find the right parameters and geometry in my complex parts.

☐ agree fully ☐ do not agree ☐ other opinion

12. During the modelling process I am able to find the right parameters and geometry in my complex assemblies.

☐ agree fully ☐ do not agree ☐ other opinion

13. The changing of my own complex components (changing parameters and geometry) and assemblies is difficult and time-consuming

☐ agree fully ☐ do not agree ☐ other opinion

14. Changing parameters and geometry of foreign components and assemblies can be done fast and immediately.

☐ agree fully ☐ do not agree ☐ other opinion

15. With regard to foreign components and assemblies it would be very helpful and desirable if there are more information about construction and structure of the components. (Documentation of the construction).

☐ agree fully ☐ do not agree ☐ other opinion

16. A description of the CAD model structure (with CATIA V5) is very useful.

☐ agree fully ☐ do not agree ☐ other opinion

17. With parametric associative systems (CATIA V5) geometry changes can be done easier than with non-parametric systems.

☐ agree fully ☐ do not agree ☐ other opinion

18. I use different kind of linkages offered by (CATIA V5) parametric associative systems within my assembly and product structure (linked drawings, geometry elements, FEM etc).

☐ agree fully ☐ do not agree ☐ other opinion

19. With the use of different linkages it is important to know the origin of the linked components (from which module, assembly, KO group).

☐ agree fully ☐ do not agree ☐ other opinion

20. The parametric associative components/assemblies sent by the suppliers are clean and structured.

☐ agree fully ☐ do not agree ☐ other opinion

The target of the questionnaire was to get important information about the experience of the designers during the work with PA CAD systems. Furthermore the questions should help to have information about the work and CAD experience of the participants. In this case it was possible to get a better understanding about the participants and their experience with PA CAS systems. In this part of the thesis the most important findings of the questionnaire will be addressed. The whole results of the questionnaire can be taken from Appendix I.

The respondents of the questionnaire were designers whose work experience was on average over 12 years. But the PA CAD system experience of the respondents was between one and five years. The result of the questionnaire was confirmation that there is a significant need for an integrated approach of PA CAD systems. 67% of the respondents were of the opinion that it is very important to concern themselves more strongly with the modelling process (Question number 6) before starting to design with PA CAD systems and therefore they have to make some preparations of how to design and structure their PA parts and assemblies (Figure 22). Furthermore this aspect confirms the issues which have been identified in the literature survey.

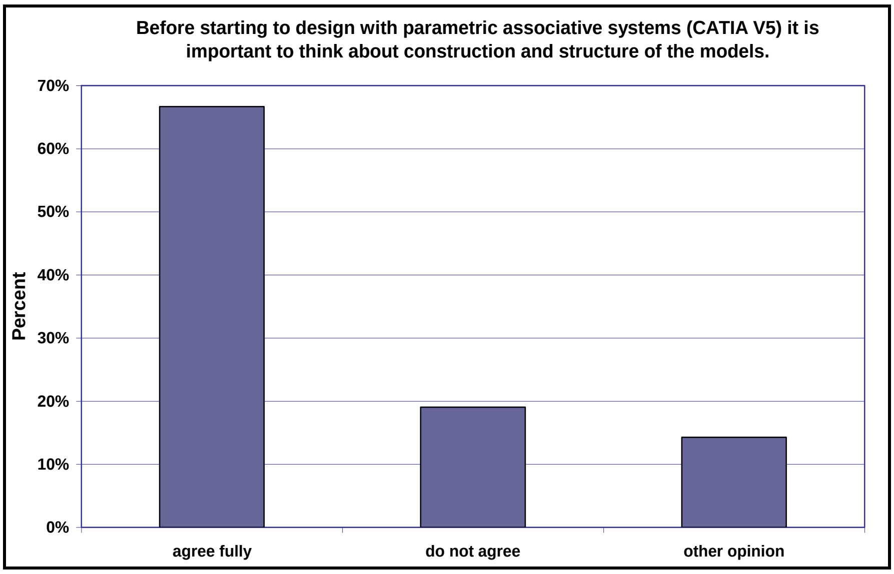


Figure 22: Question related to preparation of modelling

In addition 85% of the respondents also stated that during the preparation phase the right methods of how to identify, classify and determine the required parameters and associative relationships are missing (Question number 11). Furthermore 71% (Question number 7) of the respondents denied having an exactly defined method and approach during their work with PA CAD systems and the remaining 29% who claimed to have a method said that many of the parts produced were poorly structured (Figure 23).

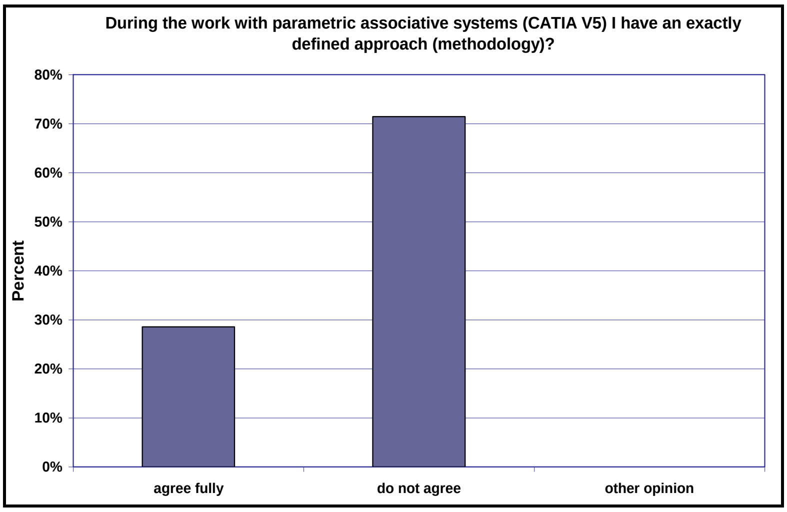


Figure 23: Question related to have a method

The main goal of this question was to identify the necessity of an integrated approach with PA. We had hypothesized that failure to apply methods would be because of time pressures, but only 19% of the designers responded that it is quite difficult to spend time for application of particular methodologies for this reason, but these answered that they would apply a certain methodology if they would have more time. Another important question was the use of the full functionality offered by PA systems and only 14% of the respondents identified that they use the possibilities which such systems offer very well (for example, fully parameterized parts and associative connections) (Question number 9). By means of this question it becomes very clear that there is also potential to improve the efficiency in the application of PA functionalities. In addition 86% of the respondents think that there is a huge potential to improve the application of PA design (Figure 24).

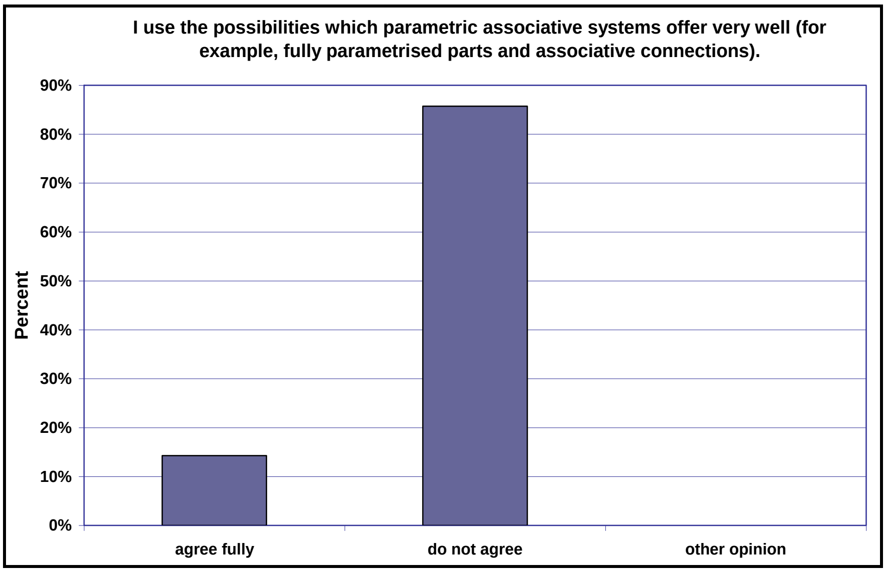


Figure 24: Use of functionalities

A lot of methods have the disadvantages to be time consuming and therefore not applicable in a real design environment. But 52% of the respondents said that they are ready to invest time in a new method of PA design system (Figure 25) (Question number 10). A further 24% would be interested in a method if it would help them during the work with PA design. In general because of the complexity of PA CAD systems there is a significant readiness of the designers to apply methods which help them to reduce the complexity and increase the transparency of the created CAD parts and assemblies. The goal of further questions was to analyse the PA modelling process used. The author asked if designers were able to identify and determine the important parameters or associative geometries.

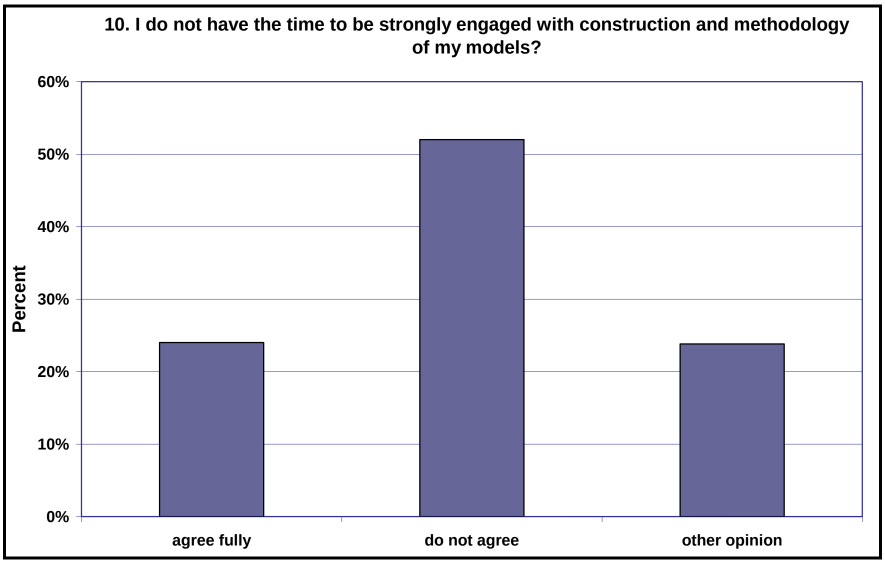


Figure 25: Time using a certain method

76% of the respondents indicated that they were not able to find the right parameters and associative relationships in large and complex CAD parts and assemblies. This problem becomes bigger if they try to change parameters and geometry of “foreign” components (these are CAD parts which are designed by other designers or by supplier). 81% of the respondents agreed that it is quite difficult to change CAD parts and assemblies created by other designers (Question number 14). These previously defined aspects confirm the relevant points of parametric design and factors which has been identified during the literature survey. The next important point was that 86% of the respondents agreed that in regard to such components and assemblies it would be very helpful and desirable if there is more information about the construction and structure of the PA part and assemblies (Question number 16). The designers appreciate the idea to have a description of the construction and structure of the PA CAD parts and assemblies.

The next important aspect was the use of associative connections between parts and assemblies. This aspect has shown the greatest gaps and weaknesses. Only 19% of the respondents agree with the question “I use different kinds of linkages offered by PA systems in my parts and assemblies (linked drawings, geometry elements, FEM etc)” (Question number 18). The reason is that designers stated that they have not the right methods to handle associative connections. Furthermore because of the lack of a method most of them have had bad experience with such associative relationships. This aspect confirms the issues which have been identified in the literature survey. The Figure below shows some of the failures which can be made during the design process with PA CAD systems. In general the results of the questionnaire confirm the issues which have been identified during the literature survey. Figure 26 shows the important results of the questionnaire, where each axis is the proportion of respondents agreeing with the statement or applying the approach.

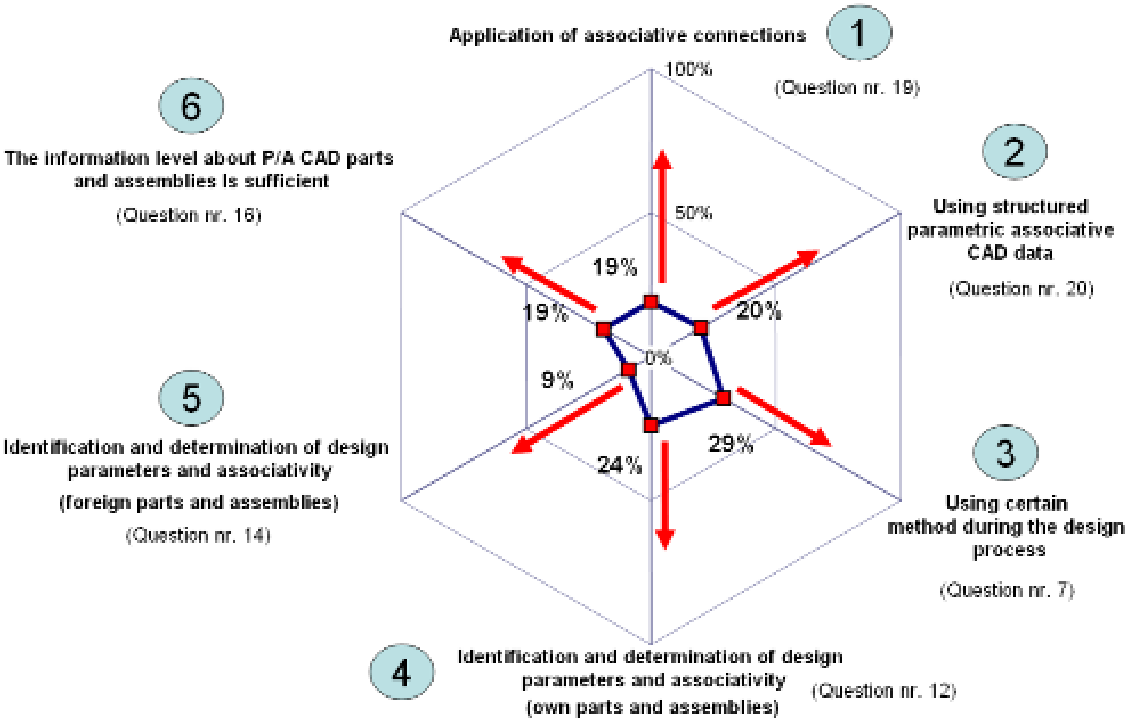


Figure 26: Important results of the questionnaire

5.2 Results of the interviews

In this part of the work the author will present the results of the interviews which have been done with CAD coaches and designers (two of the Interviews are attached in Appendix II; translated from German to English the remaining interviews are available in German in electronic form). In this phase eleven experienced CAD system coaches have been interviewed. The basic conditions of the interviews are in Table 6. The target of the questions in these interviews was to have a clear understanding of the problems, challenges and expectations of the designers of a PA CAD system. The intention was to collect information about a) the experience of CAD trainers during teaching and training of PA CAD systems (what kind of important factors did they identify); b) the observation of the CAD trainers related to the different "categories" of designers and how they approach PA CAD systems; c) the experience of the CAD trainers related to structuring of PA CAD parts and assemblies. A summary of the questions which has been asked can be found below. The most important issues and aspects of the Interviews are given in Appendix II.

The most important aspects and results of the interviews with CAD experts and coaches can be summarized as follows:

- During the work with PA systems designers have difficulties to identify, determine and represent relevant parameters and associative relationships;
- The created associative relationships are not well thought out and elaborated. Designers create many associative relationships between the geometrical entities without being aware of the consequences;
- A preliminary consideration and preparation of the created parameters and associative relationships would be a great asset for the designer. This aspect improves the identification, determination and representation of the created associative relationships;
- Designers are confronted with problems which are not related to the product but are rather related to the logical aspect (relationships between parameters and associative geometries);
- PA CAD parts and assemblies are often not well structured and therefore it is quite difficult to change them or to find relevant design information.

Environment	Automotive Industry and suppliers
Participants	11 CAD trainers and CAD support engineers
Date Collection methods	Interviewing, documentation
Time constraints	120 minutes per each interview
Team size	2 participants (researcher and interview partner)
Number of cases	11 interview partners
Total duration	2 Months (from creation phase to the analysis of interviews)
Role of researcher	Interview leader, documentation

Table 6: Basic conditions of the interviews

The results of the interviews showed the same important aspects that have been identified during the analysis of the questionnaire results. It demonstrated that most of the designers have problems in preparing the required PA design information inputs and outputs. Furthermore for most of the designers it is difficult to identify, determine and structure the parameters and associative relationships.

5.3 Analysis of existing PA CAD parts and assemblies

For a better understanding of the embodiment design process and activities the author had the unique opportunity to analyse real industrial CAD parts and assemblies which were created with PA CAD systems. One of the main characteristics of modern and capable PA design systems is that these systems allow storing of the history of the design features, called “history based design trees” of parts and assemblies. Any action, together with the data used to complete it, is recorded in the order that it occurred during the process of building a particular model. The operational parameters can be geometric entities as well as expressions. These history trees are like a documentation of the design steps and features. An analysis was carried out to investigate CAD parts and assemblies of different design departments like power-train and Body-in-White division. Different design departments store their design results like CAD parts and assemblies in a virtual product management system, which also includes the virtual structure of a product. Because of this the author was be able to analyse the following characteristics of every part and assembly:

- The different procedures used to create parts and assemblies.
- The different structures used to create parts and assemblies.
- The information stored in a part or assembly.

The goal of this step was to generate new knowledge and information about the different methods used to create parts and assemblies with PA systems. By means of analysing the design history tree it is possible to cluster the found knowledge and information in different categories. This step will help to identify a strategy for structuring the geometrical information and structural templates which can be used during the structuring process of PA CAD parts and assemblies. In this case a module with 174 CAD parts has been analysed. The first step of the analysis was to examine the complexity of the CAD parts and assemblies. This point is important because there are parts and assemblies with different levels of complexity (in this case complexity means the size of the analyzed components related to the number of features and the associative relationships of the components). Table 7 shows the different criteria for the component complexities.

Type of complexity	Number of Features	Associative connection	Percentage
Low	< 50	1	20%
Middle	> 50 < 200	< 10	30%
High	> 200	> 10	50%

Table 7: Complexity definition of the analysed parts

Type of complexity	Low	Middle	High
Standard parts (Screw, Shell etc.)	X		
Module 1: Cylinder Head			X
Module 2: Cylinder block			X
Module 3: Connection Rod		X	
Module 4: Piston		X	
Module 5: Oil Pan			X
Module 6: Crankshaft		X	
Module 7: Exhaust system			X

Table 8: Characteristics of parts with low, middle and high complexity

The next step is to open the selected CAD parts and assemblies. In the third step the data has been categorized in different clusters. The clusters in which CAD parts can be divided are low, middle and high complexity (Table 8). After clustering the CAD parts and assemblies the analysis of the parts and assemblies can be started. Furthermore it was also possible to see what kind of different structuring and design procedure existed. In this step it was also possible to make statement about “well” or “poorly” designed and structured CAD models. However, before rendering a judgement it is very important to define the criteria which make a PA CAD part/assembly “well” or “poorly” created. The following aspects have been identified:

- Identification of used and required important parameters (key-parameters);
- The way of structuring parts and sub-assemblies
- Complete naming of features used in parts and assemblies;
- Change services (i.e. is it possible to change parameters and to regenerate the CAD parts and assemblies) of parts and assemblies;
- Identification of design information inputs and outputs (references, interfaces);
- Identification of the different kinds of relationships between the parameters and CAD parts (geometrical entities);
- Identification of used rules and formulas;

The quantitative evaluation of the parts was based on the components with low and high degree of complexity. The result of analysing existing CAD parts and assemblies confirms the results of the questionnaire and interviews but also the findings during the literature survey (Table 3 on section 4.4.4→ comparisons of the same aspects and criteria). It was visible that there are tremendous problems and difficulties during the design process with PA CAD systems. In all categories of CAD parts and assemblies (less complex and more complex components) problems of identifying and determining the parameters and associative relationships has been elaborated and established. The most interesting observation was that there also have been difficulties to identify and determine the different kinds of parameters and associative relationships in the so called “less complex CAD parts”. Furthermore highly complex CAD parts and assemblies were highly lacking in the required parameters. In this case only in 8% of the parts it was possible to identify and determine the different kinds of parameters (geometrical, physical and process parameters). Another problem which has been identified was that some of the “low” and “high” complexity CAD parts were not well structured. It was also possible to show that there was an obvious problem how to structure the required parameters and design information inputs and outputs. In the different CAD part categories it also was visible that the required downstream-process information was not available. In most of the cases it was not possible to make geometrical changes of the high complexity CAD parts. The reason was that there exists complex relationships between the geometrical entities and no documentation of these relationships was available. Table 9 shows the identified factors of the analysed CAD parts and assemblies.

	Low complexity CAD parts	**High complexity CAD parts**
Aspect 2: Functional aspects		
Aspect 2.1: Parameters:		
Identification, determination of different kind of parameters is possible	21%	8%
Identification of the relationship between the parameters (e.g. a + b = c)	19%	5%
Aspect2.2: Associativity:		
Identification, determination and representation of different kinds of associativity (unidirectional and bidirectional)	26%	13%
Aspect 3: Structural aspects of CAD modelling process		
Identification of design information inputs and outputs are clear structured and visible	24%	11%
The features are labelled and named	22%	7%
Aspect 4: Process related aspects		
Downstream process parameters are available and clearly structured	15%	6%
CAM and CAE required data are available	0%	0%

Table 9: Identified problems of analysed parts and assemblies

5.4 Conclusion

The results of the literature review and Descriptive Study showed that there is a need for an integrated approach for working with PA CAD systems. The developed approach should consider some general and specific requirements. Pahl and Beitz [PAHL/BEITZ, 2002] described the following general requirements which are important during the development of methods in design engineering: a) methods should be easily taught and learned; b) methods must not rely on finding solutions by chance; c) methods must be compatible with the concept; d) methods must reflect the findings of cognitive psychology and modern ergonomics; e) methods must encourage a problem-directed approach; f) methods must foster inventiveness and understanding. The aforementioned requirements will be considered during the Prescriptive Study in the next chapter. This Prescriptive Study is the next step of the DRM according to Blessing and Chakrabarti. The main role of the Prescriptive Study is to develop a framework for a model or theory which is based on the results, assumptions and findings of Descriptive Study I. This stage serves to identify or describe methods and processes and will elaborate an approach of working with PA systems. The specific requirements which should be considered during the definition of a PA CAD method can be summarised as follows:

- The developed approach should consider a preliminary phase which helps to prepare the relevant information (parameters and associative relationships) which is necessary to create a full PA CAD model. A characteristic of this phase is that it should be completely independent to a certain CAD system. The target of this phase is to have a clear understanding of the existing relevant parameters and associative relationships between the geometrical entities. Furthermore the relevant parameters (geometrical parameters like length, physical parameters like material and process parameters like tolerances) should be identified, determined and prepared very carefully. This phase also helps to think about the relevant associative entities and their relationships to each other. The results of the questionnaire showed that most of the problems during the creation of associative relationships are caused by creating associative connections without thinking about further process steps and the consequences of such relationships. The identified important aspects and indicators are:
    1. To identify and determine the relevant parameters;
    2. To represent the relationships between the different kinds of parameters;

3. To identify and determine the relevant associative entities;
4. To represent the associative relationships between the geometrical entities;
5. To reduce the complexity of PA CAD models;
6. To structure the relevant parameters;
7. To structure the relevant associative entities;
8. To structure the design information inputs and outputs of CAD models;

- The developed integrated approach should consider the structural aspects of PA CAD parts and assemblies. That means identifying how it is possible to create a structure which considers the relevant design information input and outputs. The main target of this approach should be to arrange and integrate the relevant PA design information.
- The developed integrated approach should consider the different levels of 3D CAD modelling. This aspect contains the consideration of "top down" (CAD assembly design) or "bottom up" (CAD part design) design.
- The procedure of the developed approach should consider the different phases of the product development process (from concept to detail design).

Based on the finding from the Descriptive Study I the next chapter will explain the developed PA approach (Prescriptive Study).

6 Prescriptive Study: The development of an integrated approach for design with PA CAD systems.

This chapter of the thesis will explain the developed method for designing using PA CAD systems, called PARAMASS (**PARAM**etric **ASS**ociative) based on the identified factors and indicators in the Descriptive Study I. To achieve the full potential of PA CAD design systems especially in view of the complexity of the CAD parts and assemblies in an industrial context such as the automotive industry it is important to have a clear understanding of how to use such CAD systems. This chapter presents an integrated approach to PA (PA) CAD systems (PARAMASS) and demonstrate the general requirements of an integrated PA approach. This section presents the different phases and sub-phases of the developed PARAMASS approach. By means of designing different components from an automotive power train (e.g. piston pin, piston and intake valve assembly, cylinder block and head) the different phases of the developed integrated PA approach will be demonstrated and presented.

6.1 3D design approaches

This section of the work will explain the important approaches for 3D modelling in an industrial environment. The explanation of these approaches is important because the newly developed PA approach considers these aspects of the modelling. There are two different approaches which are used by designers during their design process with PA CAD systems. The first approach is based on assembly modelling which can be divided into a “bottom-up” and a “top-down approach”. The second approach is based on single CAD part modelling. For a better definition and explanation of the above mentioned approaches the characteristics and important issues related to approaches will be explained by means of an engine assembly. This assembly has been created by means of the developed PA approach (PARAMASS), which is also explained in the following chapter.

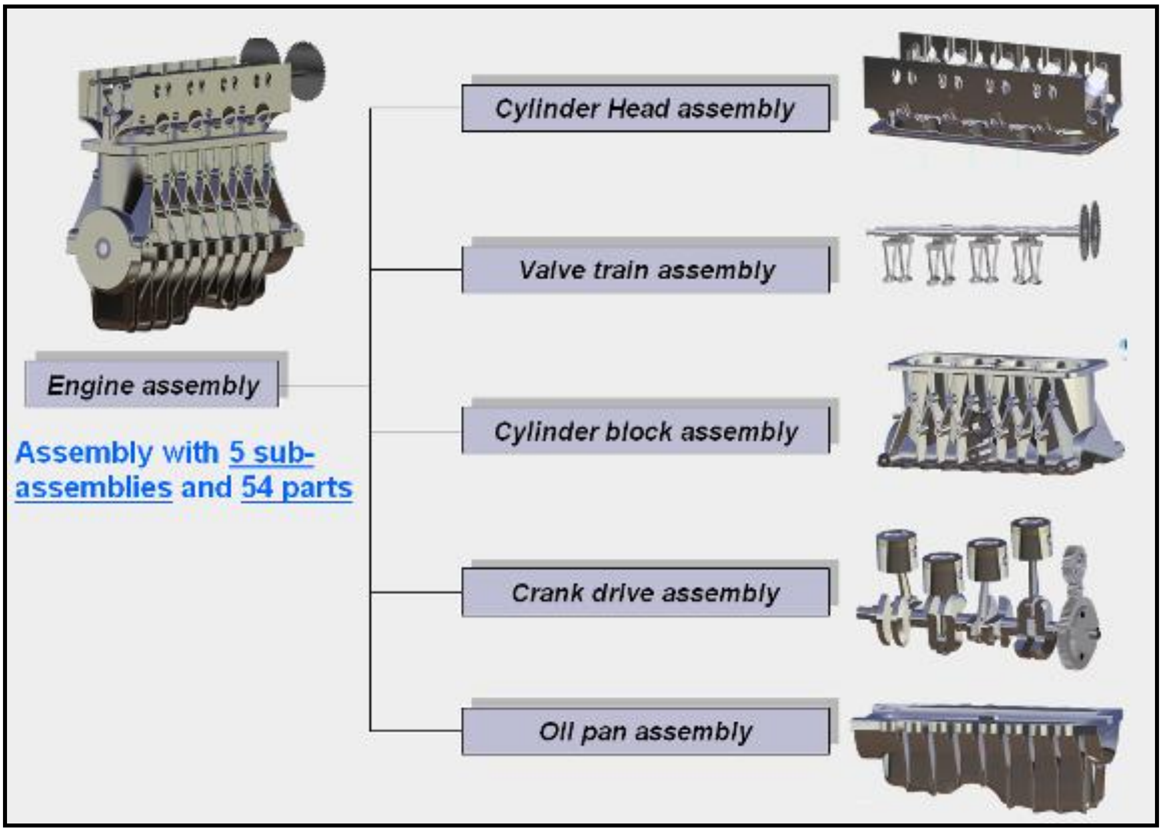


Figure 27: Product structure of an automotive engine

Figure 27 represents an example which is created to demonstrate the application of the developed approach with a PA CAD system. In this example the structure of the engine contains 5 different subassemblies which include further single parts. At the top level of the engine structure there is the whole engine as an “engine assembly”. The subassemblies which are on the next level are: cylinder head assembly, valve train assembly, cylinder block assembly, crank drive assembly and oil pan assembly. Each of these assemblies is described by different kinds of parameters. The challenge is to prepare, identify, determine and structure the required parameters in an integrated product development process environment. That means enabling the design process participants to exchange the relevant parameters in an efficient way. Furthermore, in a PA CAD design “environment” it is very important to structure the required design information inputs and outputs clearly. Because of that an integrated approach is needed to enable the design process and participants to create parametric CAD parts and assemblies where the important design parameters are well defined, determined and structured (Figure 28).

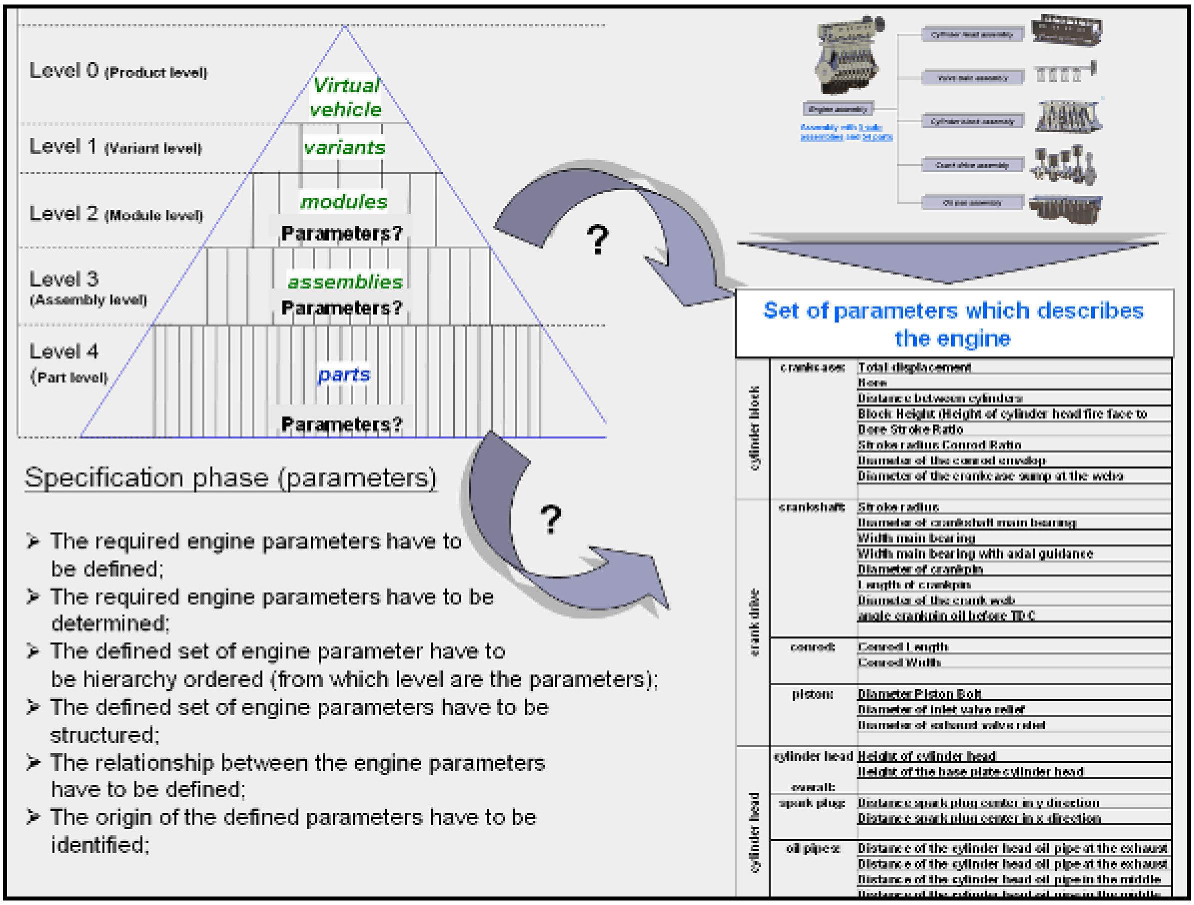


Figure 28: Hierarchy structure and parameters of an engine

Every engine assembly level contains geometrical parameters which are relevant for the different engineering teams. In case of engine development it must be ensured that the designers are able to find the right design parameters in a clear and well structured way. Furthermore the different participants of the engineering teams like the CAE and CAM departments should be able to get the "right" required engineering parameters without additional efforts. Related to working with an engine structure there are the following aspects which have to be addressed.

- The required engine parameters in different hierarchy levels have to be defined and determined;
- The defined set of engine parameters has to be hierarchically structured;
- The hierarchy relationships between the engine parameters have to be defined;
- The origins of the defined parameters have to be identified;

In addition to the above mentioned aspects it is also important to explain the content and procedure of assembly and part modelling which is the basis of working with PA design.

The next section will define the general characteristics of assembly and part design in 3D modelling environment.

6.1.1 Assembly modelling

During the structuring of PA CAD components one can distinguish between design information inputs and outputs which are available on assembly and part levels. Most mechanical products are not single piece parts but assemblies of several components. This is necessary not only for the function needed or mechanical power transmission requirements but also for products that consist of different materials, and parts with varying sizes and shapes that are best produced separately [SHAH, 1991]. Moreover the production and maintenance of complex parts becomes easier when they are made by assembling simple components. The assembly process is used for producing finished products in almost all industries. Assembly design considers the following aspects: a) kinematics, b) interchangeability of parts, c) geometric arrangement of components to produce compact packages, d) Assemblability and disassemblability, e) collision and interfaces, f) tolerance allocation to produce the proper quality function [AIT, 1995]. The assembly model is needed to drive several engineering analyses and applications like interference detection between parts, motion simulation, constraint satisfaction, assembly analysis, and assembly manufacturing planning [AIT, 1995]. According to Shah [SHAH, 1991] the information that needs to be captured and represented at the assembly level by an assembly modeller includes the following:

- Hierarchical relationship (assemblies, sub-assemblies, components, features, etc.);
- Mating conditions (geometric constraints, fits, contact, etc.);
- Component / sub-assembly positions (global or relative);
- Degrees of freedom (possible relative motions of parts or sub-assemblies).

Positioning of assembly entities is achieved by coordinate referencing, which requires all positioned entities to have their own coordinate system, or – preferably, because more flexible in case of model changes – by mating conditions, e.g. facing or coplanar faces, co-axial axes, coincident points. Shah [SHAH, 1991] also emphasize the importance of assembly features that allow assembly creation at a higher level by storing mating and constraint information and thus enabling parametric feature modelling functionality rather than geometric constraint handling at shape level. Analogously to the generalised CAD model architecture, an assembly model, a part model and a shape model is to be represented with uni-directional associations between their entities. On assembly level, a part structure model is required representing a hierarchy of parameterised parts and assemblies. Figure 29 presents an assembly and its different contents on an abstract level.

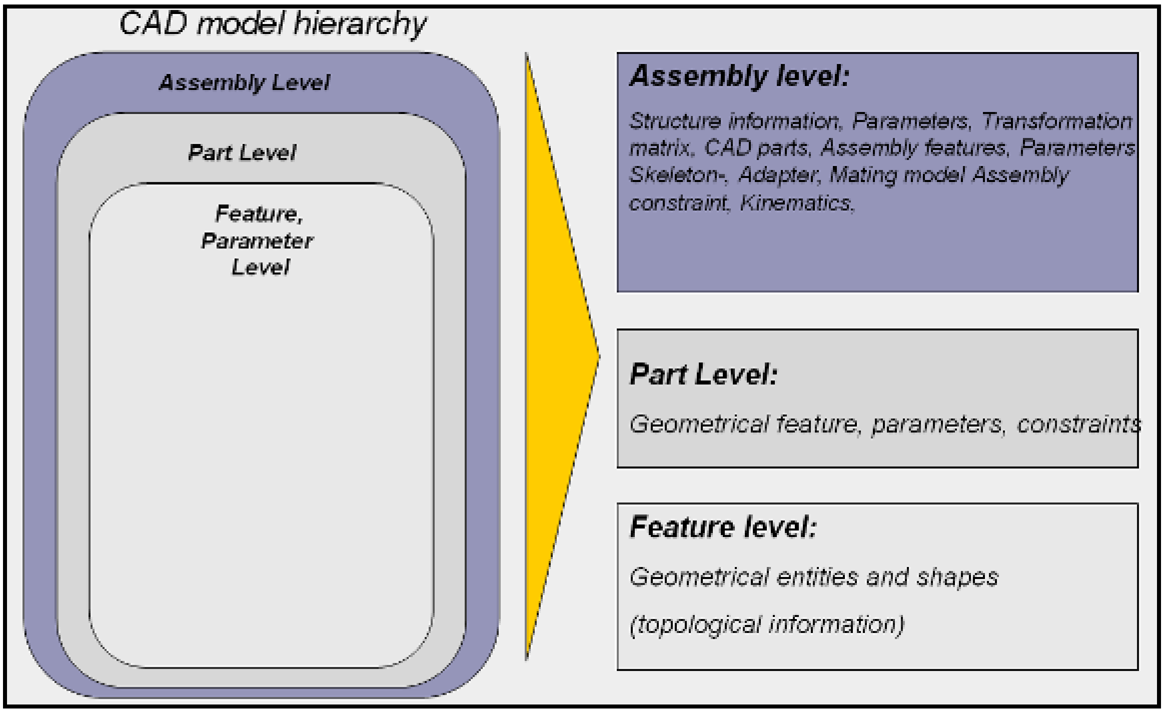


Figure 29: Representation of the CAD model hierarchy levels

During the modelling process of assemblies there are two different kinds of approaches. These approaches are “top-down” or “bottom-up”. Figure 30 presents the different approaches. The top-down approach is preferred by most designers for conceptual design, since then the design of the assembly starts at a high level of abstraction. Assembly design does not always require detailed design of constituent parts and subassemblies. Hence the design can be carried out in terms of abstract concepts, and this helps the designer in validating some of the design concepts prior to their implementation. Ideally a top-down design environment support transitions from high-level, conceptual assembly models stressing the function of the assembly to detailed models of the individual components.

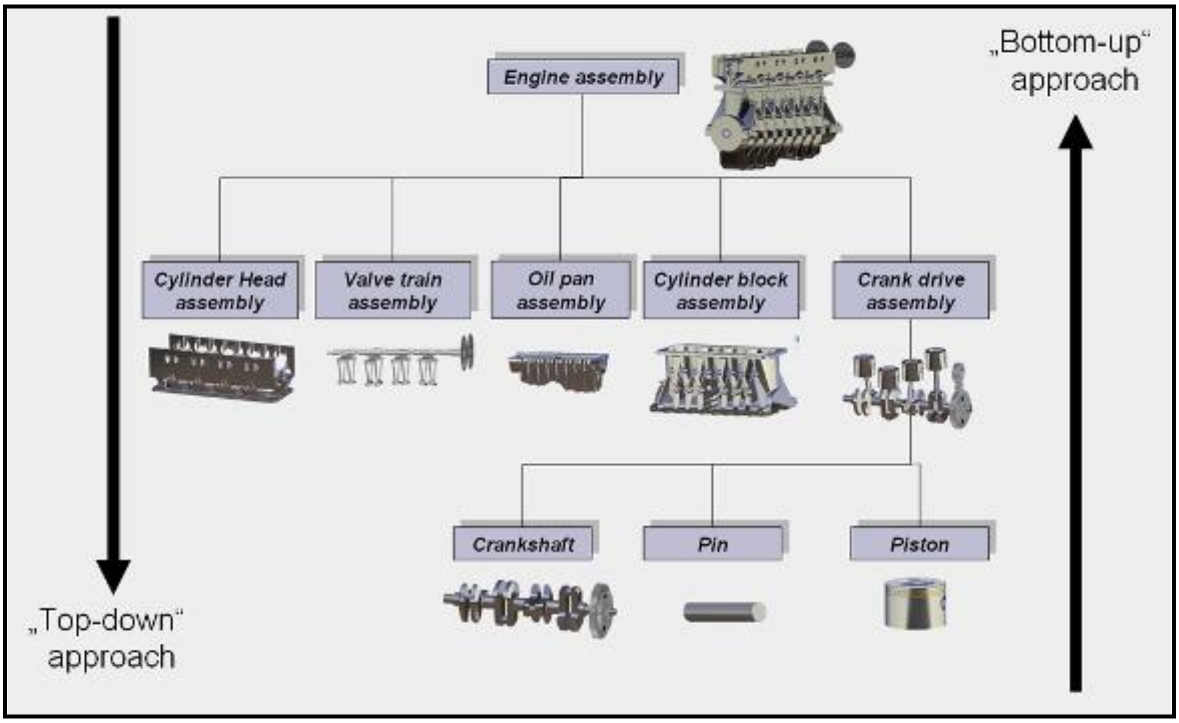


Figure 30: Assembly design “top-down” and “bottom-up” approach.

The abstract specification of a design can usually be captured in a structure consisting of the major components or subsystems of the desired product and their desired interfaces, associative relationships, and constraints [ROLLER, 1990]. In some design domains, the specification may be expressed by means of numerical performance parameters and expressions; generally, however, no numerical, qualitative specifications are needed. After the initial specification, the design process proceeds from the abstract to the concrete.

Abstract concepts are decomposed into more concrete ones, and new interfaces, relationships and constraints are created among them [ROLLER, 1990]. At some stage, it becomes useful to use a geometric representation to express the desired relationships between the concepts introduced [PRATT, 1998]. For a few values critical for delivering the desired function of the design, the actual dimensions and coordinate values are unimportant; the geometry mainly serves to specify the geometric constraints among the parts. The design system should support the creation of abstract geometry, where important and less important characteristics of the geometry are explicitly distinguished from each other, and the designer can choose the level of detail of the representation according to the particular requirements of the design task [SHAH, 1991].

During the later stages of the design process, new, increasingly concrete concepts and their relationships are introduced, and the abstract geometry is modified to take them into account. In this process, the aspects of the abstract geometry which initially were treated as being unimportant are refined and more precisely defined [AIT, 1995]. The critical aspects of the geometry, which were already specified, are observed as rigid constraints. Hence, the previous characteristics of abstract geometry must be treated as further design constraints for the future requirements of the less detailed and unspecified characteristics [ROLLER, 1990]. At the same time, the abstract geometry must not unnecessarily limit the freedom of the designer in the later stages.

One important aspect of top-down design is that it permits the designer to concentrate on one sub-problem of the design at a time [AIT, 1994]. During the design process, the focus of the designer shifts from conceptual design to the basic design of the various subsystems involved in the conceptual solution and, finally, to the detailed design of each subsystem and each component. The sequence of focus changes can be interpreted as an instance of the design methodology that the designer applies to this design; therefore, to enhance the value of the resulting model, the shifts of focus should be made explicit in the model [AIT, 1994]. The design system must support focusing on some particular aspects of the design and, in particular, capture the sequence of focus changes in the model representation.

The “bottom-up” approach involves piecing together systems to give rise to grander systems, thus making the original systems sub-systems of the emergent system. In a bottom-up approach the individual base elements of the system are first specified in great detail. These elements are then linked together to form larger subsystems, which then in turn are linked, sometimes in many levels, until a complete top-level system is formed [SHAH, 1990]. This strategy often resembles a "seed" model, whereby the beginnings are small but eventually grow in complexity and completeness. However, "organic strategies" may result in a tangle of elements and subsystems, developed in isolation and subject to local optimization as opposed to meeting a global purpose. The “bottom-up“approach starts with designing a single CAD part or a single CAD assembly at the lowest level of the product structure. At the end of the design process of the created single components all the CAD parts and assemblies will be merged to a new model or an assembly. That is also the reason why we talk about a bottom-up design.

6.1.2 Part modelling

The next aspect of the PA CAD approach is the part modelling. The representation of a part model requires a feature structure with parameterised features as design elements and Boolean operations as structural elements [AIT, 1995]. The representation of the corresponding shape model is shown in Figure 31. A feature structure of a part can be understood as a tree-like hierarchy of instantiated design feature objects in a certain status with a corresponding shape. Every inner node of this structure represents a design step with a corresponding resulting shape model. Every additional inner node results in a new shape model. The final part model results in the final shape model [AIT, 1995].

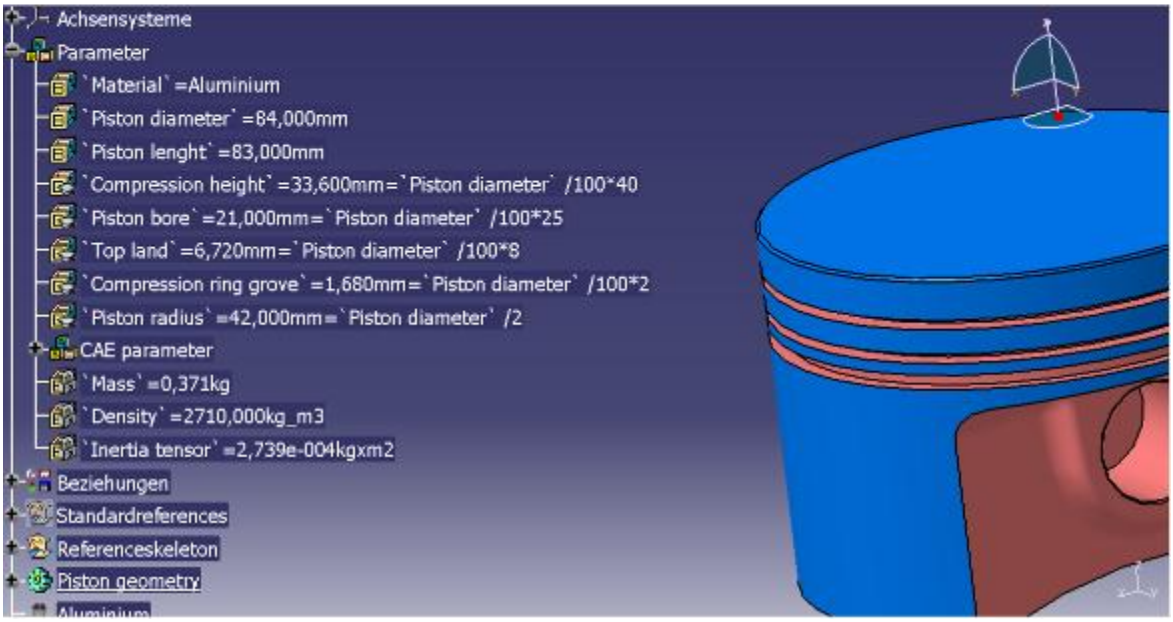


Figure 31: Part design of a piston with its history thee and parameters

Anderl describes [ANDERL, 1998] part modelling as a building of a geometric object for presenting the properties of a work piece. The result of this step is the complete description of a geometrical model. Parameters can also result from the calculation of one or several constraints defined on one or several parameters [ROLLER, 1990]. The totality of parameters, constraints or constraint system, and resulting values shall be referred to as the parametric model of a part or assembly model. The parametric model is an important aspect of model alteration. The specific behaviour of a parametric model is strongly dependent on the constraint solving philosophy the CAD system incorporates, namely fully parametric or variational [SHAH, 1991]. This behaviour cannot be "transferred". Nevertheless, the parametric model is the modelling foundation and must be represented and transferred as part of a structure-oriented model exchange. The representation of parts and features as parametric entities requires additional representation items. The following parameter information must be represented for each entity [SHAH, 1991]:

- Unique identifier, i.e. an identifier assigned by the system;
- Name, i.e. an identifier assigned by the user;
- Type, e.g. numeric, Boolean, string, etc.;

- Unit, distinguishing e.g. millimetres from inches;
- Value, i.e. the current result from the last (and consistent) calculation of the constraint system or a simple value assignment.

After the definition of different approaches related to the 3D-modelling the next section will present the developed integrated PA approach. Furthermore many of the aspects which have been explained about assembly and part modelling will be used in the next section. Therefore it is important to explain the important key aspects of the above mentioned approaches (Assembly and part modelling approaches).

6.2 PA design approach requirements based on the Descriptive Study I and literature survey

The complete results of the identified challenges and factors are reported in Chapter 5. In general it can be summarised that the results of the literature survey and Descriptive Study I showed the following important aspects related to the development of the PA approach:

- A **specification phase** is necessary to have an understanding about available parameters and associative relationships. The relevant parameters and associative relationships have to be structured in a clear way. This step should help the designer to "think" about possible parameters and associative relationships. Furthermore the preliminary consideration of possible parameters and associative parameters helps to prepare the relevant information which is necessary to create a full PA CAD model. The characteristic of this phase is that it is completely independent of CAD system. The target of this phase is to have a clear understanding of the existing relevant parameters and associative relationships between the geometrical entities Furthermore the relevant parameters (geometrical parameters like length, physical parameters like material and process parameters, like tolerances) have to be identified, determined and prepared very carefully. This phase helps to think about the relevant associative entities and their relationships to each other.
- The **structuring aspect** of the created CAD parts and assemblies has also been identified as an important issue. The developed integrated approach should consider the structural aspects of PA CAD parts and assemblies. That means how is it possible to create a structure which considers the relevant design information input and outputs. The main target of this phase is to arrange and integrate the relevant PA design information inputs and outputs in a structured way. The integrated approach which will be presented will consider the factors and indicators of the Descriptive Study I and will include the following targets and aspects:
    - To identify and determine the relevant parameters in a systematic way;
    - To represent the relationships between the different kinds of parameter;
    - To identify and to determine the relevant associative entities in a systematic way;

- To represent the associative relationships between the geometrical entities;

Table 10 summarises the identified aspects and problems during the work with PA systems. Furthermore it shows the selected solution approach for tackling the identified problems.

Identified aspects and problems	**Proposed Solution (Novelty approaches)**
Consideration of preparation phase which helps to plan, prepare and understand the important parameters and associative relationships during the design process with PA CAD systems;	Introduction of a **specification phase** to prepare, identify and determine the important parameters and associative relationships
Parameters:	
Identification and determination of geometrical, physical and process related parameters;	Development of **PSM** approach **(Parameter Structure Matrix) New approach**
Associativity:	
Consideration and identification and determination of associativity (unidirectional and bidirectional) ;	Development of **ASM** approach **(Associative Structure Matrix) New approach**
Identification of associative connection between geometrical and non geometrical relationships (i.e. point,. line, shapes and solids)	
Structural aspects of CAD modelling process	Introduction of a **specification phase** to structure important parameters and associative relationships
Identification of structural design inputs and outputs; Structuring development of rough and machined CAD parts and assemblies;	Development of **structure** of CAD parts and assemblies (New approach) (PA Part and Assembly Structure, **PAPS and PAAS approach), (New approach)**
Creation and modelling phase of mechanical parts	Migration of a **Creation and modelling phase** of the parts and assemblies
Creation of the reference geometry	Development of **standard parts and assembly structures** of CAD parts and assemblies
Creation of the rough part	
Creation of the finish part	

Table 10: Identified aspects and the new approaches developed solutions

6.3 Development of the PARAMASS approach based on the V-process model

During the development of an integrated approach the next aspect which has to be clarified is the representation of its procedure or the process model of the developed integrated approach. The research showed that the processes which were available at the automotive company did not provide sufficient guidance to the designers as the processes are very generically defined and do not reflect the necessity of PA design. Because of issues of confidentiality it is not possible to say more about the processes. Every process model is purpose oriented and is an information reduced presentation of reality. Process models allow the representation of processes and their activities with each other. Furthermore it supports to analyze, plan, accomplish and document the required information and steps [BICHLMAIER, 2000]. During the model of product development processes there are two different aspects which should be considered: a) Computational models which describe the process in a formal, analytical manner. Thus they can be used, for example, in determining the critical path for a given process. b) Illustrative models which enhance the (common) understanding of a process by depicting its elements and influences. The presented approach in the following thesis is an illustrative model. According to Stetter [STETTER, 2000] the use of illustrative models is recommended because product development occurs in an environment of uncertainty and ambiguity where precise data for i.e. mathematical modelling is generally not available. During the first implementation of the approach the aspect related to the process model was not considered by the researcher. The result was that the first idea of the approach was based on a work flow diagram. This work flow diagram was not accepted by the designers. The consequence was the first trial completely failed. The designers mentioned that it is important the method should consider the different stages of the product development process and also the different level of information (from rough to detailed design). Therefore they also suggested the V model process which considers this aspect is much more suitable than a simple "Work flow diagram". The presentation of the procedure model can be based on:

- Elementary thinking and action procedure which are based on micro logic. These are cycles of analysis, synthesis and assessment. (e.g. TOTE model: Test-Operation-Test-Exit, DPS: Discursive Problem Solving and PDCA Cycle: Plan-Do-Check-Act);

- Operative working procedure which is based on macro logic (e.g. Problem solving process according to Ehrenspiel);
- Phase based working process which is based on macro logic and describes a general procedure of something like VDI Guidelines (i.e. Guideline 2221 and V-model);

The approach which is selected in the following thesis is based on a phase model according to the V-model. The V-Model is a systems development model designed to simplify the understanding of the complexity associated with developing systems. From an engineering point of view PAHL and BEITZ describe systems as technical artefacts that are artificial, concrete and mostly dynamic and consist of sets of ordered elements, which are interrelated by virtue of their properties [PAHL/BEITZ, 1996]. In addition, Lindemann denotes system borders as well as inputs and outputs that connect the system to its surrounding [LINDEMANN, 1999].

The V-model is a graphical representation of the systems development lifecycle (Figure 32). It summarizes the main steps to be taken in conjunction with the corresponding deliverables within general system design framework. The V-model is a process model that represents the sequence of steps in project life cycle development. It describes the activities and results that have to be produced during product design and development. The left side of the V-model represents the decomposition of requirements, and creation of system specifications. The right side of the V-model represents the integration and modification of parts and their verification. The V-model deploys a well-structured method in which each phase can be implemented by the detailed documentation of the previous phase. The model recognizes that there are two types of maturation in system development.

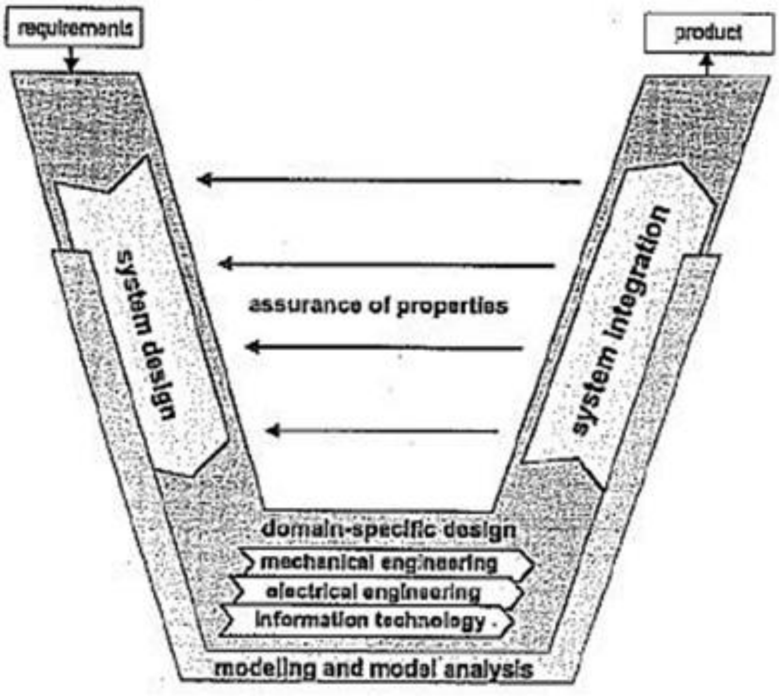


Figure 32: VDI guideline 2206

In V-model representations the time and maturity move from left to right. Iteration is essential in system development and all iteration is done vertically. The left leg of V-model core investigations centre around what concept is best and what architecture is best for that concept. For example, commercial consumer electronic products usually face the dilemma as to whether batteries should be standard, unique, replaceable, or not. In the right leg of V-model, core downward investigations are directed at investigating integration and modification anomalies to determine their root cause and to correct them.

During the development of the integrated approach described here all the designers interviewed mentioned that the method should consider the different stages of the product development process and that the process normally starts from a concept level and then the CAD models become more detailed. The relevant factors of the V-model in describing these aspects are:

- The V-model is used in different industries, including automotive and aerospace. Furthermore the V-model is a very well known approach which has been used and applied by the designers in their product development process and is therefore familiar to the designers.

- The V-model approach considers the concept level of the product development process, from which a system concept description (usually described in a concept study) is produced;
- The V-model considers the system level and produces a system description in performance requirement terms;
- The V-model allows a division at subsystem/component level, which produces first a set of subsystem and component product performance descriptions, then a set of corresponding detailed descriptions of the products' characteristics, essential for their production.

There is a good correspondence between these characteristics and the requirements for a model for the novel PA approach. The designers stressed the importance of the different levels of the product development process and product structure to be implemented inside the method. By means of the V-model it was possible to integrate the different levels of the product development process and structure from the concept to the detail phase. Furthermore, the different levels of the system and components (assembly or part level) are integrated inside the developed approach. This was an aspect which was initially not considered during the method development process by the author but after the first trial of the developed method was one of the important aspects which has been identified and required to be incorporated by the designers. The next section will define the different steps of the method.

6.4 Outline of a novel PA Process Model

The approach presented in the following section is based on three different main phases which comprise the top-level of the developed approach (see Figure 33). These phases are: 1) Specification phase; 2) Structuring and creation phase and 3) Modification phase. At a second level of the integrated approach there are further six sub-phases, as follows:

Phase 1: Specification phase

1.1. Identification and determination of parameters for CAD parts and assemblies.

1.2. Identification and determination of associative relationships for CAD parts and assemblies.

Phase 2: Structuring and creation phase

2.1. Structuring and creation of parameters and associative relationships on part structure level

2.2. Structuring and creation of machined parts on associative assembly structure (Reference part, rough part and finished part)

Phase 3: Modification phase

3.1. Modification of CAD design parameters and associative relationships

3.2. Modification of the created structure

Figure 33 shows these phases and sub-phases in the V-model and they are explained in detail in the following sections.

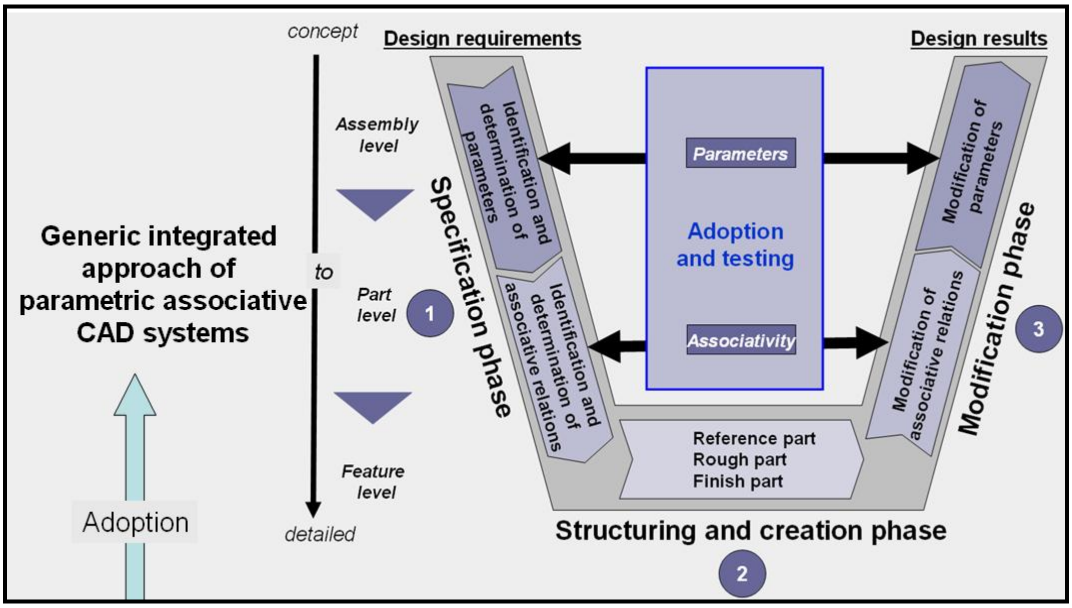


Figure 33: The novel PA Process Model

Figure 34 presents the different issues and challenges which have been integrated in the developed PA process model. For example during the Descriptive Study I it was possible to identify that a lot of parameters and associative relationships are created with little attention and without any preparation of the required information. Therefore a phase is developed which is able to specify all these parameters and associative relationships. Furthermore during the specification phase is should also be ensured how to identify determine and present the different kinds of parameters and their relationships to each other. These examples should only demonstrate that every phase of the developed approach is based on the results of the Descriptive Study I and the literature survey. In the following sections the reasons for creating these phases will be explained in more detail.

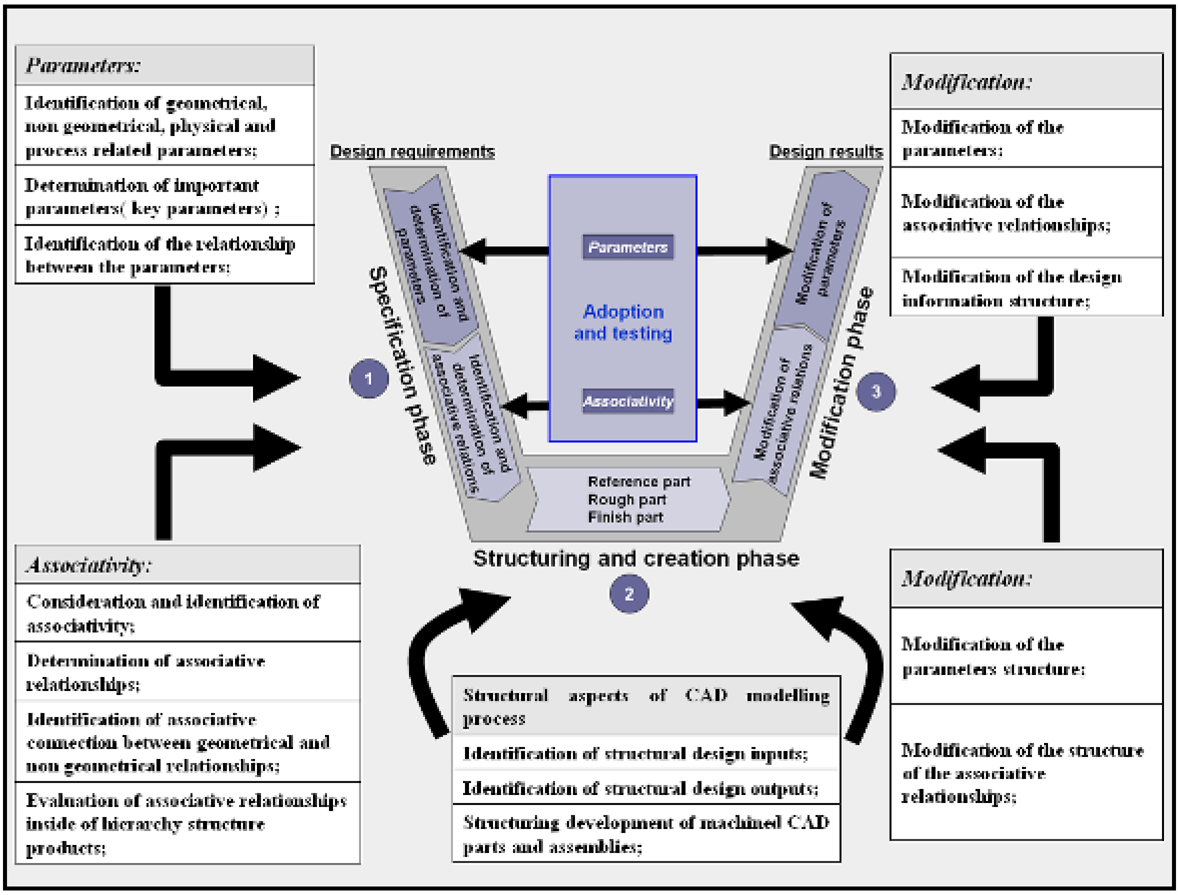


Figure 34: Implementation of Descriptive Study I and literature survey findings in the PA process model

6.5 Phase 1: Specification phase

The specification phase is one of the important aspects of design methods in widespread use. For example, the methods according to Pahl and Beitz [PAHL/BEITZ, 1984], VDI 2222 [VDI 2222, 1997] and VDI 2206 [VDI 2206, 2004] contain this important step. Pahl and Beitz described this phase as product planning and clarifying the design task, involving product planning, analysis of the market situation and product proposal. In this phase all product ideas and solutions are defined, identified and determined. The result of all these tasks is the elaboration of a "specification list". It is necessary to identify, define, determine, structure and arrange the important aspects which describe the product and their sub-elements. The results of these steps are to gain information which can be converted into useful and essential design knowledge. In the case of PA CAD design systems the results of the literature survey and Descriptive Study I have shown that the working process requires a certain "thinking process" which is necessary to prepare and understand the further steps of the modelling process with this kind of CAD system. This step is analogous to the specification phase in design processes. From the point of view of the author the specification of the relevant parameters and required associative relationships needs a fundamental analysis, otherwise the created CAD parts and assemblies will be confronted with difficulties in later product development steps. Furthermore according to the VDI guideline 2209 [VDI 2209, 2006] working with parametric CAD systems needs preparatory work. Therefore it is important to have a specification phase which helps to identify, determine, structure and arrange the relevant parameters and associative design information which are necessary to design full PA CAD parts and assemblies. Experience has shown that careful analysis and formulation of problems are the most important steps of the systematic and generic working approach [PAHL/BEITZ, 1984]. The specification phase of the PA approach is divided into two different sub-steps. These are a) identification and determination of parameters and b) identification and determination of associative relationships. Another aspect which is also important during the specification phase is how to capture the identified knowledge and information during this phase. In the conventional design processes, Pahl and Beitz suggest using checklists to document the required information (requirement list) [PAHL/BEITZ, 1984]. The selected approach to capture the gained "knowledge" and information during the specification phase of PA design information is a checklist which has the form of a Parameter Structure Matrix (PSM) and the Associative Structure Matrix (ASM).

The examples here are based on a piston, piston pin and the assembly of an intake valve. The next section will present the different stages of the developed PA approach by means of the above mentioned examples.

6.5.1 Identification and determination of parameters

The relevant parameters during the design process with PA systems can be classified in three different categories:

- *Geometry parameters*: These are geometry indicators like size, height, breadth, length, and diameter or object properties which classify the product. These parameters are also known as “driving parameters”. By modification of driving parameters the generation of a new variant of the CAD model is possible [KOLLER, 1994].
- *Physical parameters*: The physical parameters define further properties of the CAD model. These are e.g. material of the CAD model. Combined with the geometrical parameters the physical parameters can be the basis of calculations and analysis [KOLLER, 1994].
- *Process parameters*: These are parameters which define the selected process of the selected technology. Process parameters can be the NC-processing data or heat treatment requirements [KOLLER, 1994].

The proposed procedure for the identification and determination of the different kinds of parameters during the design process with PA CAD systems is given in Figure 35.

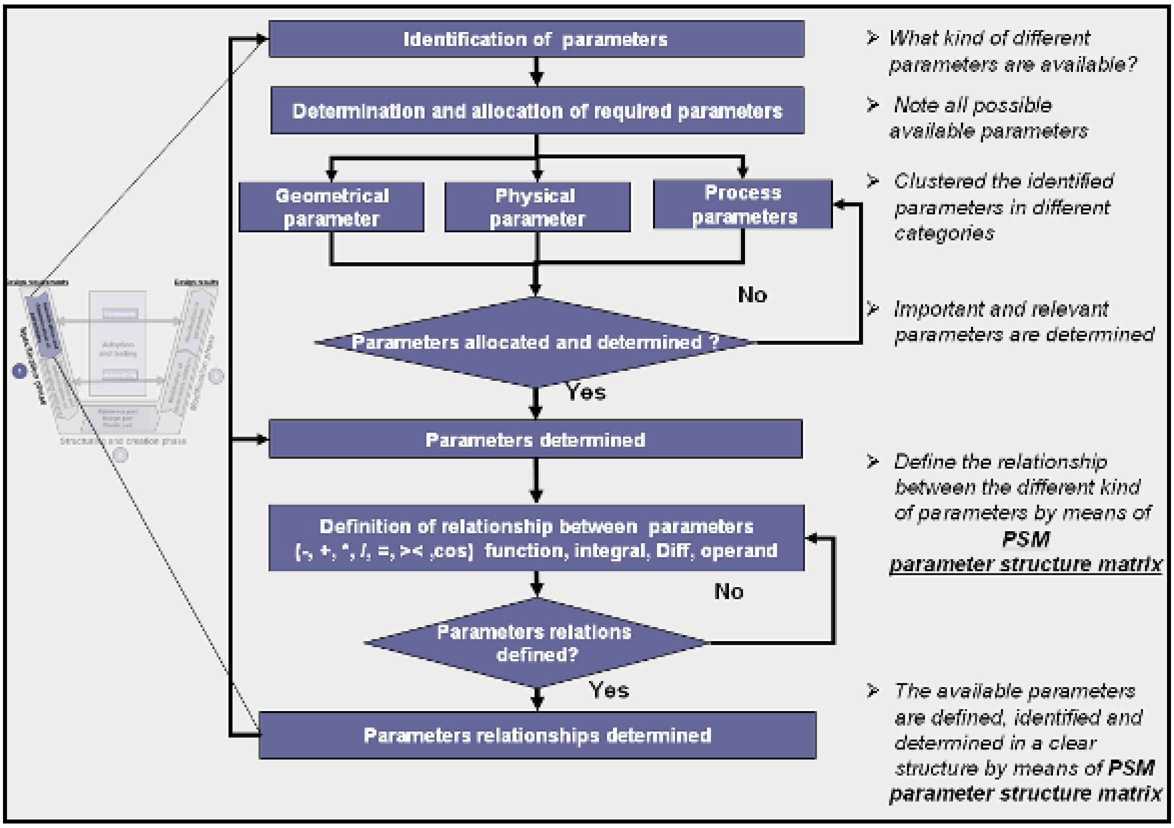


Figure 35: Procedure of identification and determination of parameters.

Furthermore there exist also relationships between the different kinds of parameters. These relationships can be arithmetical, logical and geometrical constraints [VAJNA, 1998]. Arithmetical relationships are the normal mathematical formula and operations like plus, minus, radical and trigonometric function. Logical relationships can be used in combination of string operations (AND, OR, IF, IF NOT etc.) for representation of different model conditions (i.e. IF D>20 then C=1 else C=3) [VAJNA, 1998].

The starting point of the identification and determination of parameters is the definition of all possible parameters in the current design stage. In case of designing a piston pin for example the parameters which describe the geometrical artefact are the length, inner diameter and the external diameter. Further parameters which are also required for the downstream processes are material, derived weight, density, centre of gravity, inertial tensors and contact surfaces between pin and the piston. Furthermore from the manufacturing aspect of the piston pin there are parameters like tolerances, surface finish and process steps (i.e. centring, turning and boring). For a better capturing and collecting of the above mentioned parameters and their relationships to each other a checklist is defined which is based on the **Parameter Structure Matrix (PSM)**. Figure 36 presents the PSM of the piston pin.

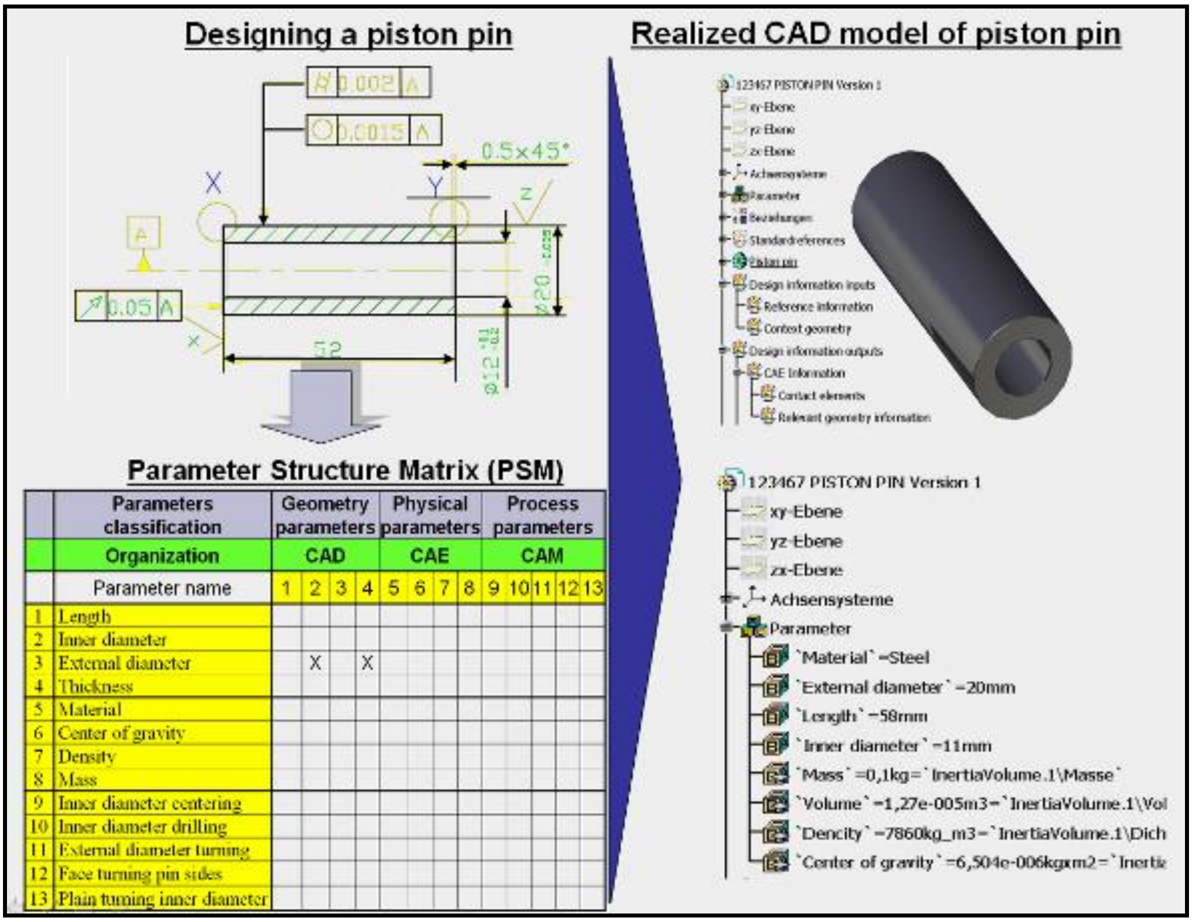


Figure 36: Specification phase of the piston pin parameters

The PSM is materialized as an nxn adjacency matrix of geometry, physical and process parameters with their relationships to each other and with identical row and column headings. Furthermore the defined parameters are clustered (clustering is a valuable technique for examining the structure of a system). The clustering technique applies graph-theoretic cluster algorithms to reorder the rows and columns of the matrix by grouping highly related nodes, called clusters, in three different organizational categories which are CAD, CAE and CAM engineering. These three different categories have been identified during the Descriptive Study 1 in which 67% of the respondents agreed that because of the associative relationships between the geometrical entities and downstream processes working with PA systems requires a closer collaboration between design participants. The framework of the PSM is based on the logic and structure of the Design Structure Matrix (DSM) approach. The DSM methodology emerged in the early 1980s as scholars demonstrated how graph theory can be used to analyse complex engineering projects. Steward showed how the sequence of design tasks could be represented as a network of interactions [STEWARD, 1981]. The DSM materialized as an nxn adjacency matrix of nodes and relations with identical row and column headings. A Design Structure Matrix (DSM) can represent the abstraction of the relations among components of a product, teams concurrently working on a project, activities or tasks of a process, and/or parameters within the system. Furthermore by means of abstraction it is possible to find a higher level interrelationship, that is, one which is more generic and comprehensive. Such a procedure reduces complexity and emphasizes the essential characteristics of the problem and thereby provides an opportunity to search for and find other solutions containing the identified characteristics. So abstraction supports systematic thinking. In Steward's model, nodes represent individual design tasks, and relations represent information flows, thereby creating a DSM of the activities or process domain. DSMs have also been used to represent and analyze technical artefacts where nodes represent system component DSM. The nodes and relations differentiate the types of DSMs. There are two main categories of DSMs: static-based and time-based. Each category contains two types of DSM; component-based DSMs and organizational or team-based DSMs are static, while activity-based DSMs and parameter-based DSMs are time-based. The developed Parameter Structure Matrix (PSM) is a static based. A static-based PSM consists of nodes that are independent of time, i.e. all nodes exist simultaneously. Thus, the ordering of rows and columns reflects groupings, not time flow. The nodes in static-based PSM are part or assembly design parameters within the product structure. Steward showed how the sequence of design tasks could be represented as a network of interactions [BARTOLOMEI, 2007]. A DSM can represent the abstraction of the relations among components of a product, teams concurrently working on a project, activities or tasks of a process, and/or parameters within the system. Furthermore by means of this abstraction it is possible to find a higher level interrelationship, that is, one which is more generic and comprehensive. Such a procedure reduces complexity and emphasizes the essential characteristics of the problem and thereby provides an opportunity to search for and find other solutions containing the identified characteristics. So abstraction supports systematic thinking [BARTOLOMEI, 2007]. The demonstration of PSM approach will be done by means of different PA CAD components which have different sizes. The first example which is selected to demonstrate the PSM approach is the example with the assembly of the engine intake valve. The assembly of the valve module assembly includes the intake valve, the valve spring, the upper valve spring retainer and the valve collet. In the case of designing an inlet valve the parameters which describe the geometrical artefact are valve stem diameter, valve stem cotter, throat valve seat, total valve seat face thickness, height of valve seat, height of valve seat face, head diameter, throat angle, valve seat angle, total length and grinding length of the valve. Furthermore the above mentioned geometrical parameters can vary for different engine types with different cylinder bore diameters. In this case the PSM can be used to identify, determine and document these kinds of geometrical relationships and dependencies. In case of the inlet valve the PSM approach can also be used to develop a catalogue of modular valves for different engine types and families. Furthermore the PSM approach helps to understand the different parameters which are relevant for the design process of the intake valve and there is a documentation of the different kinds of parameters and their relationship to each other. Figure 37 presents the PSM approach for the assembly of the intake vale.

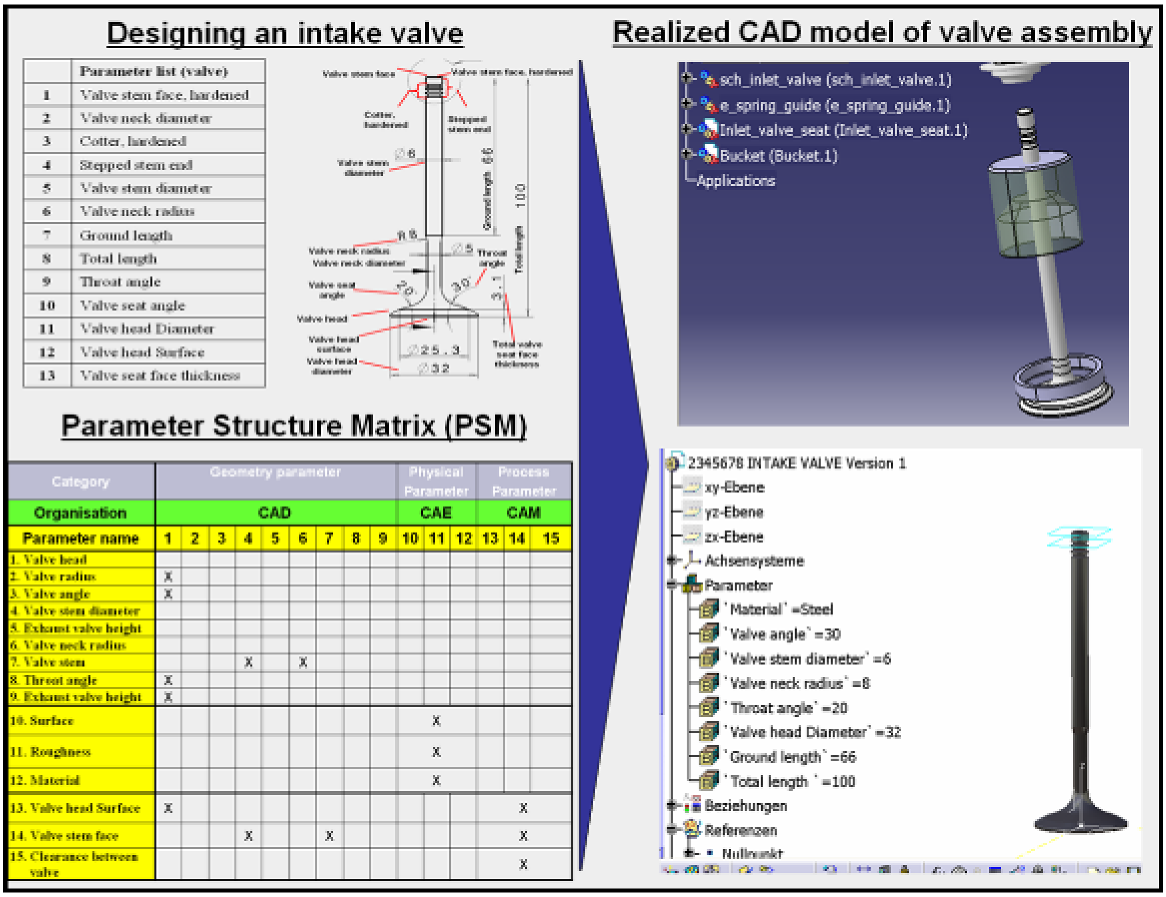
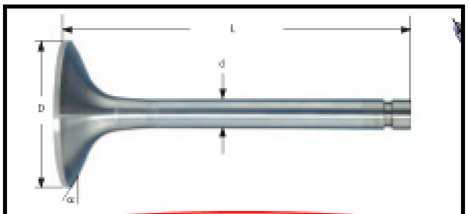


Figure 37: Specification phase of the valve assembly parameters

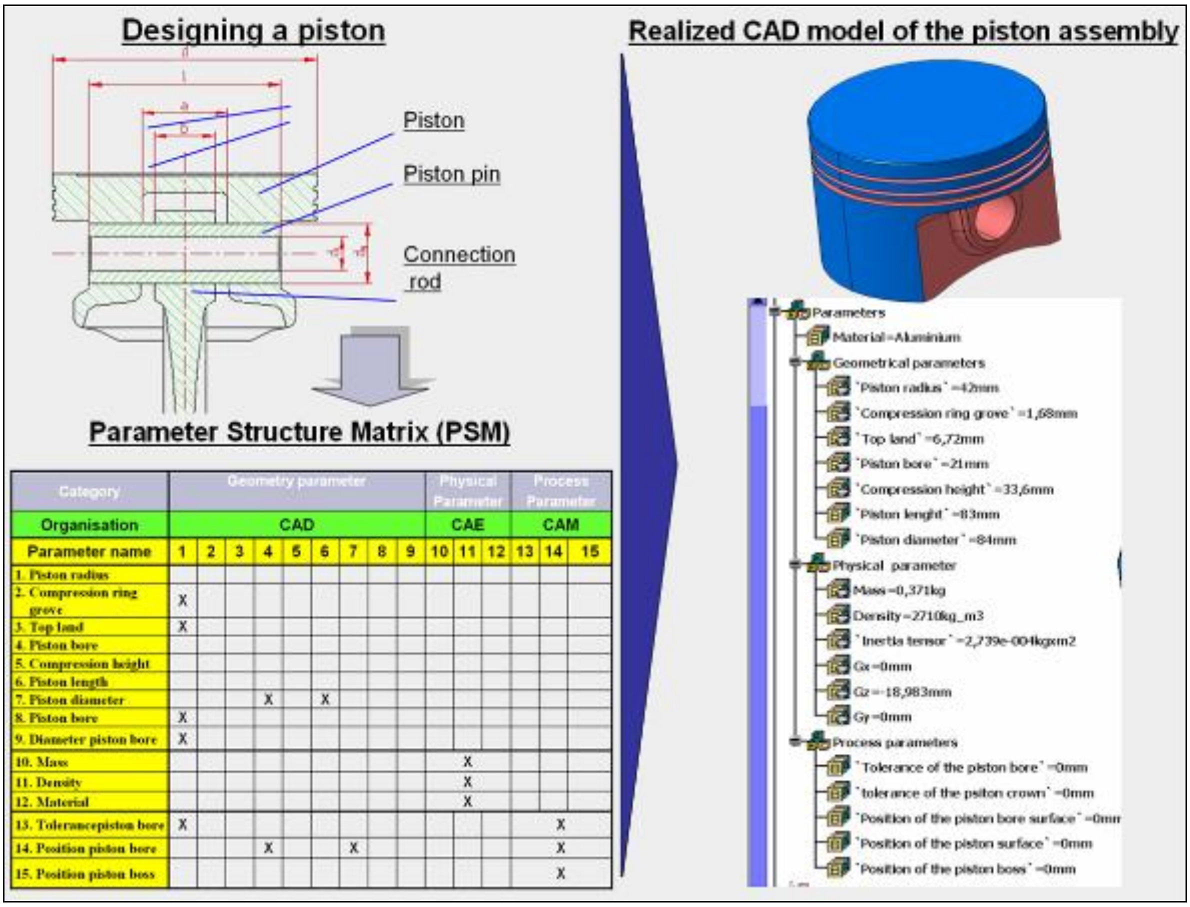
Based on the PSM approach for every different engine module it was possible to define the relevant parameters of the engine valves. Figure 38 demonstrates the different sizes of an engine valve which is created for different cylinder bores.



B = Bore diameter	D = Head diameter	d = Stem diameter	L = Overall length	Valve seat angle
Ø82,6	37,4	8	116,6	45°
Ø82,6	37,4	8	116,6	45°
Ø93	41	8	120,7	45°
Ø75	34	8	104	45°
Ø75	34	8	98,7	45°
Ø76,5	35,9	7	89,9	45°
Ø76,5	29,5	6	100,9	45°
Ø79,5	36	8	95,1	45°
Ø79,5	36	7	95,5	45°
Ø81	36	8	96,8	45°

Figure 38: Definition of different valve geometry and position based on engine bore

A further example which was selected for the application of the PSM approach was the PA design of a piston. This example will be used for the evaluation process of the developed PA approach (see Figure 39).



Category	Geometry parameter									Physical Parameter			Process Parameter		
Organisation	CAD									CAE			CAM		
Parameter name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Piston radius															
2. Compression ring grove	X														
3. Top land	X														
4. Piston bore															
5. Compression height															
6. Piston length															
7. Piston diameter				X		X									
8. Piston bore	X														
9. Diameter piston bore	X														
10. Mass											X				
11. Density											X				
12. Material											X				
13. Tolerancepiston bore	X													X	
14. Position piston bore				X			X							X	
15. Position piston boss														X	

Figure 39: Designing a piston by means of the PSM approach

By means of the created PSM structure it was possible to capture all the relevant parameters of the designed engine (Figure 40). Furthermore it enables designers to exchange the relevant parameters with other CAD designers and departments. Figure 403 demonstrates the scheme of the different PSM created for the engine assembly. A selected summary of the identified parameters can be taken on the next page (Table 11).

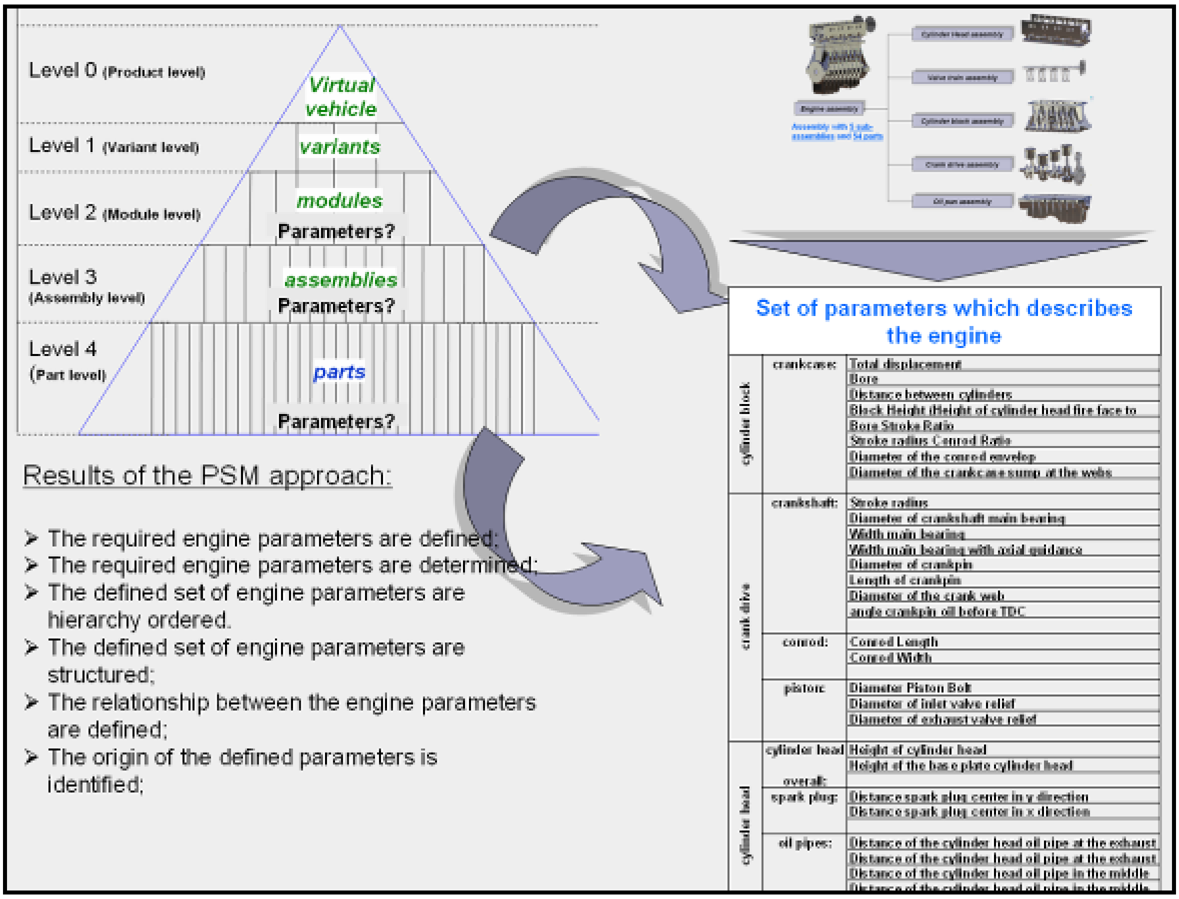


Figure 40: Schematic representation of the different PSMs of the engine assembly

Group	Parameter	Unit	Value
Basic parameter	Cylinder capacity	[l]	2
	Number of cylinders		6
	Cylinder bore	[mm]	88
	Cylinder distance	[mm]	98
	Stroke	[mm]	93
	Capacity	[kW]	260
	Torque	[Nm]	800
	Specific power	[kW/l]	58,8
	Specific torque	[Nm/l]	180,9
Cylinder block	Bank offset x	[mm]	18
	Bank offset y	[mm]	15
	Bank angle	[mm]	45
	Height of the block	[mm]	249,15
	Height of the crank case	[mm]	
	Oil pan flange	[mm]	70
	Web width	[mm]	11
	Crankshaft bearing diameter	[mm]	75
	Length	[mm]	550
	Flange surface	[mm]	236
	Flange surface gear box	[mm]	252,5
Cylinder block interface	Flange surface engine block left	[mm]	130
	Flange surface engine block right	[mm]	130
	Angle flange engine block left	[°]	30
	Angle surface engine block right	[°]	30
	Cylinder length	[mm]	155
	Thickness cylinder liner	[mm]	1,75
	Thickness cylinder	[mm]	167
	Plane water pump	[mm]	12
	Plane camshaft drive chain	[mm]	15
	Chain camshaft bank 1	[mm]	46
	Chain camshaft bank 2	[mm]	244
	Belt plane	[mm]	24
	Depth water jacket	[mm]	65

Group	Parameter	Unit	Value
Crankshaft	Crank shaft main bearing diameter	[mm]	70
	Breadth main bearing	[mm]	29,8
	Thickness shell main bearing	[mm]	2,5
	Breadth shell main bearing	[mm]	24
	Radius shell main bearing	[mm]	1,6
	Diameter crank pin	[mm]	59
	Breadth crank pin	[mm]	36
	Thickness crank pin shell	[mm]	2
	Breadth crank pin shell	[mm]	15
Connection rod	Con rod bearing diameter	[mm]	59
	Con rod bearing diameter outside	[mm]	63
	Thickness con rod shell	[mm]	2
	Breadth con rod shell	[mm]	15
	Con rod bearing breadth	[mm]	14,5
	Con rod breadth	[mm]	18
	Con rod bearing box diameter	[mm]	32
	Con rod bearing box diameter outside	[mm]	34
	Thickness con rod bearing box	[mm]	1
	Breadth con rod bearing box	[mm]	20
	Con rod length	[mm]	157
Cylinder head	Surface cylinder head	[mm]	251,15
	Max. thickness cylinder head	[mm]	2
	Thickness cylinder head	[mm]	2
	Man. thickness cylinder head	[mm]	1,9
	Cylinder head fixing bolts	[mm]	12
	Distance cylinder head screw inlet side	[mm]	46,5
	Distance cylinder head screw exhaust side	[mm]	46.5
	Diameter cylinder head screw	[mm]	8
	Plane cam shaft drive	[mm]	10
	Plane chain drive	[mm]	21
	Angle flange suction unit	[°]	23
	Middle of the channel inlet side in x direction	[mm]	12
	Middle of the channel inlet side in y direction	[mm]	12

Table 11: Set of identified parameters by means of the PSM approach

6.5.2 Identification and determination of associative relationships

After the identification and determination of the required parameters it is then important to clarify the identification and determination of the required associative relationships between the geometrical entities. Related to the design process, associativity describes the fixed relationships between geometrical entities and objects. These associative relationships include for example the connection of 3D models and down-stream process related elements. (The connections between 3D models and down-stream process are finite element models, toolpaths and other derived information). The product geometric entities include assemblies, components, solids, faces, edges, vertices, surfaces, curves and points. For a better understanding this section will first explain the different definitions of the above mentioned terms.

The starting point of the procedure to identify and determine the associative relationships between the geometrical entities is the investigation of the geometrical interface and determined parameters of the CAD components. For the investigation of the geometrical interfaces it is necessary to analyse the CAD components which are in the surroundings of the created CAD component. The target of this step is first to identify the surrounding geometry and in the next step to determine the associative entities and objects which are relevant for the creation of the reference model. During the determination of the associative relationships it is necessary to distinguish between geometrical entities which have an impact on the PA CAD component geometry and those which have no impact the geometry. There are two different kinds of associative relationships between the geometrical entities. These are “driven” and “not driven” relationships. “Driven” relationships have a direct impact on the CAD components which are based and connected with them. A “not driven” associative relationship doesn’t have associative impacts to the other geometry and describes only the geometrical environments. In case of the design of the piston pin the relevant parameters have been identified in the step before. Now the geometrical interface analysis should help to identify the important geometrical interface of the piston pin. For a better capturing and collecting of the above mentioned associative connections between the geometrical entities a checklist which is based on an **Associative Structure Matrix (ASM)** has been created. The ASM approach contains the associative relationships between the geometrical objects and entities. The framework of the ASM is again based on the logic and structure of the DSM. The ASM is materialized as an nxn adjacency matrix of CAD parts and associative relations with identical row and column headings. Furthermore, by means of the ASM the relationships between the associative geometrical entities can be clustered. In the Associative Structure Matrix (ASM) the "X" in a cell is used to indicate the coupling and relationships between the different associative CAD parts or assemblies which are in the surrounding of the created CAD part. The goal of the ASM is the identification and determination of the geometrical entities which are used in the reference model. In case of the associative design of a piston pin the analysis has shown that there is a relationship between the piston pin, the piston and the connecting rod (see Figure 41). The determination of geometrical entities which describe the content of the reference model of the piston pin is from the piston and the connecting rod. The geometrical entities which have been identified and determined are the position, diameter and horizontal axis of the connecting rod eye boss and the piston. By means of the ASM approach the different kinds of associative relationships between the geometrical entities can be identified and determined during the design process with PA CAD systems.

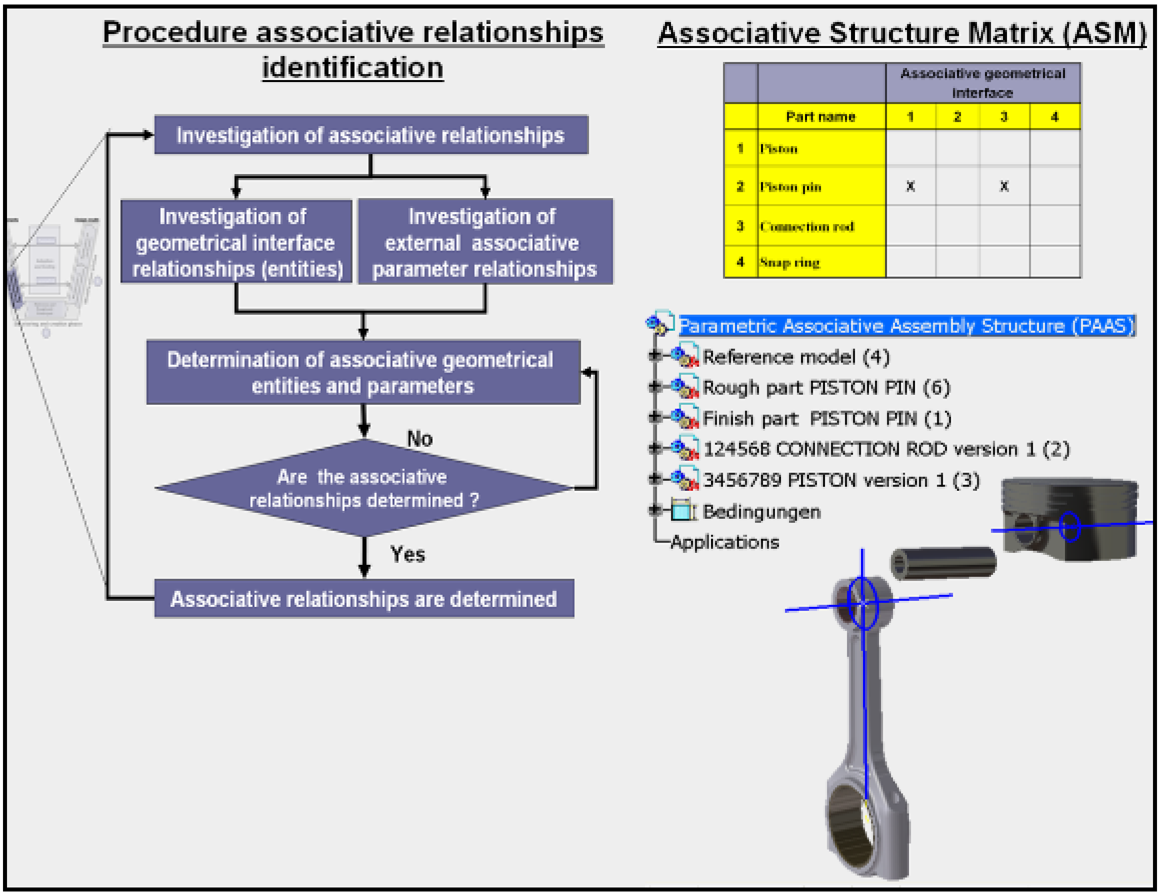


Figure 41: Identification of associative relationships between the pin and piston

In addition the clustering of the associative relationships helps designers to get a better understanding of the available associative relationships between the geometrical entities and in this way designers are able to plan how to integrate the identified geometrical entities in their created CAD parts and assemblies. Furthermore with the ASM approach designers are also able to create the conceptual architecture of their reference model. That means that ASM helps to define and create the reference models on the different levels of the complex product structure. In case of designing an associative architecture of an engine the ASM approach helps to identify and determine the relevant associative relationships of the different system levels. Furthermore the methodological preliminary working stages of creating associative relationships between geometrical entities can be supported through the ASM approach.

Related to the identification of the associative relationship of the next example which is the valve assembly it was possible to create the associative relationships in a systematic and methodological way. That means especially during the early stages of the intake valve design it is quite important to be able to modify e.g. the intake valve angle and position. Therefore these relevant parameters have been created by means of direct associative links between the geometry and the reference model of the intake valve. In this case it was possible to change the relevant parameters like intake valve angle, the clearance between the valves, the inlet valve height (which is linked to the piston bore and position), the valve position clearance and the intake valve diameter by means of associative relationships. Furthermore by means of the created ASM approach it is possible to catch these relevant associative relationships directly without a long searching process. It enables the direct changing process of the relevant parameters and associative relationships. Figure 42 shows the associative relationships between different CAD components. The position of the valve assembly is controlled through the associative connection with another CAD model which contains the basic geometry of the valve assembly like the position and diameter of the valves.

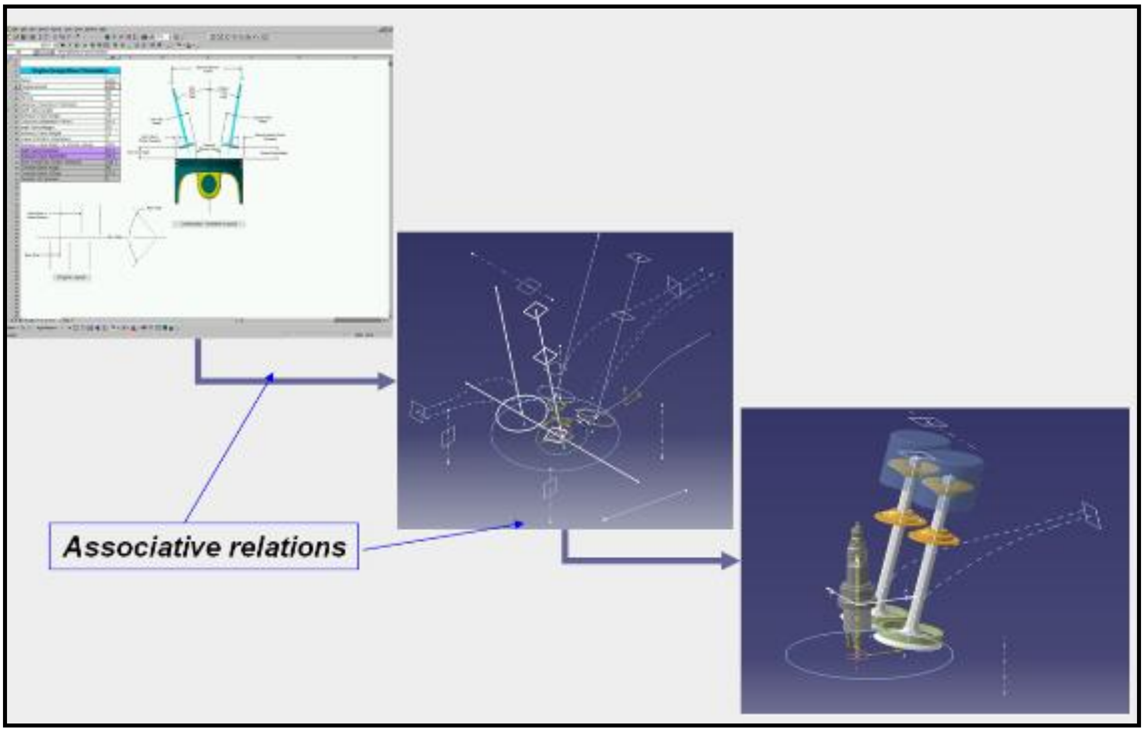


Figure 42: Definition of different associative relationships of the valves

By means of the developed ASM approach it was possible to identify all the relevant associative geometries for the engine structure. Furthermore it was possible to have a better control over the relevant associative parameters and relationships. That means that the problems with the identification and determination of the relevant associative geometries have been improved. The reason therefore is that the designers are able to use the ASM approach for the determination of the geometrical interfaces between their CAD components. Furthermore the ASM approach also allows “thinking” and capturing of the associative relationships between their CAD parts and assemblies. This aspect is a very important one because most of the designers claim that in the past they had enormous problems to have the full picture about the associative relationships of their components. Especially in a concurrent engineering environment where the interaction between the designers is one of the most important issues, Figure 43 demonstrates the results of the designed engine structure by means of the ASM approach. Furthermore it is possible to identify the relevant associative relationships between the different modules (modules are defined as a set of assemblies inside of the engine structure, related to the following example there exist 5 different modules which are: cylinder head assembly, valve train assembly, cylinder block assembly, crankshaft assembly and oil pan assembly) of the engine which are hierarchically ordered.

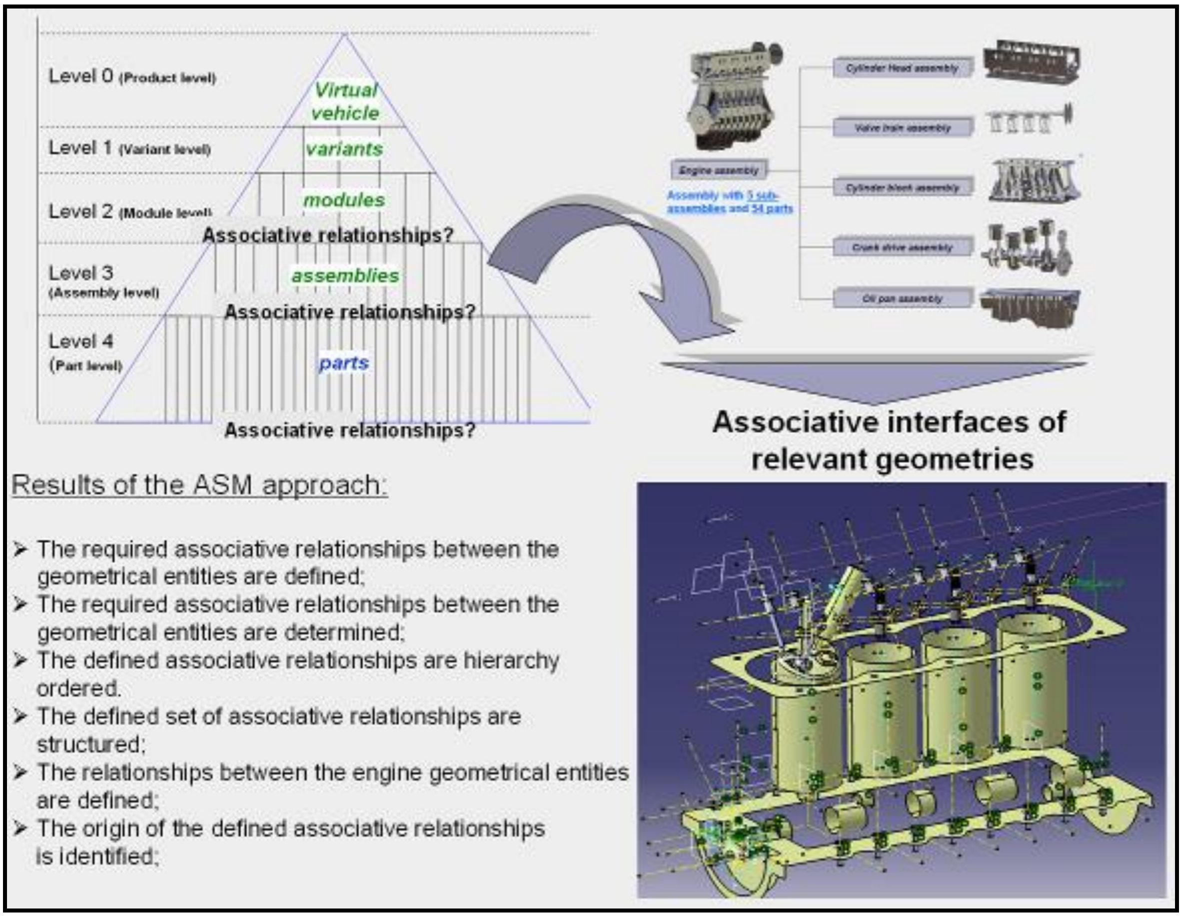


Figure 43: Results of the ASM approach of the engine structure

6.5.3 Using "spread sheets" for PSM and ASM approach

During the application of the PSM and ASM approach it was important to have a "simple" approach to handle the created data. Furthermore for the designers it was also important to be able to share the PSM and ASM matrix with the other departments. Therefore the most suitable way without having the effort to develop a separate application for the designers used spread sheets in Excel. Furthermore the application of the Excel was known by all the designers. Appendix VI presents the source code in Excel.

The next section will present the next phase of the developed new PA V-model which is related to the structuring and creation aspect.

6.6 Phase 2: Structuring and creation phase

After the identification of the required parameters it is then important to identify the associative relationships between the components. By means of the structuring and creation phase it is possible to structure the parameters and associative relationships identified between the geometrical entities in the specification phase. The PSM and ASM approaches help identify, determine, document and cluster the different kinds of relationships between the geometrical entities. The structuring aspect of CAD parts and assemblies is one of the important most aspects of these approach identified by both the literature survey and the Descriptive Study I.

The next important point was that 86% of the respondents agreed that with regard to “foreign” components and assemblies it would be very helpful and desirable if there could be a pre-defined structure for the CAD parts and assemblies. Furthermore, many of the respondents claimed that because, CAD parts and assemblies are poorly structured they have difficulties in modifying them. In addition to these, the design information required by the downstream process partners is not well structured. The designer appreciates the idea of using pre-defined CAD parts and assembly structures which consider these requirements. The purpose of structuring technical systems is the decomposition of systems in smaller subsystems and by means of structuring it is possible to reduce the complexity of a system and to concentrate the available information from the environment. In the case of PA CAD design it is very important to structure the parameters identified and the relationships between the geometrical entities. By means of structuring the parameters and geometrical entities it is possible to increase the reusability of the created CAD parts and assemblies. Furthermore because of the structuring of design parameters and geometrical entities, engineering and process partners are able to find the information available in the created CAD parts in an efficient way. The presented approach is based on fixed pre-defined PA assembly and CAD part structures which have the following goals:

a) to increase the transparency of the parameters and associative relationships;
b) to increase the reusability of the created parts and assemblies by means of established predefined structures;
c) to standardize the structure of the created PA CAD parts and assemblies for machined components;

d) to enable the possibility to structure the determined parameters and associative relationships;
e) to define a hierarchical order of the different design information inputs and outputs;
f) to integrate the clustered and classified parameters and associative relationships in the CAD parts and assemblies;
g) To enable designers and other design participants to find the required parameters and associative relationships by means of a predefined structure.

The predefined PA structures are divided into part and assembly modelling categories. According to Shah the assembly model is needed to make "*some engineering analyses and applications like interference detection between parts, motion simulation, constraint satisfaction, assembly analysis and assembly manufacturing planning" [SHAH, 1991]*. Furthermore the information that needs to be captured and represented at the assembly level by an assembly modeller includes the following targets:

a) assembly and sub-assembly positions (global or relative coordinate systems);
b) mating conditions (i.e. geometrical relationships);
c) Hierarchical relations (assemblies, sub-assemblies, components and features) [SHAH, 1991].

Positioning information and a system of part spanning constraints is also included. During the modelling process of assemblies there are two different kinds of approach. The selected approach for the following work is based on the "top-down" approach. This means that the structures which are predefined are created and given top-down [SHAH, 1991]. The starting point of the procedure to structure and create the parameters and associative relationships is to identify if the CAD component is a single part or an assembly. After this the predefined structure of a CAD part or an assembly can be selected. In the final step the design information inputs and outputs which contain the parameters and associative relationships can be arranged and created (Figure 44).

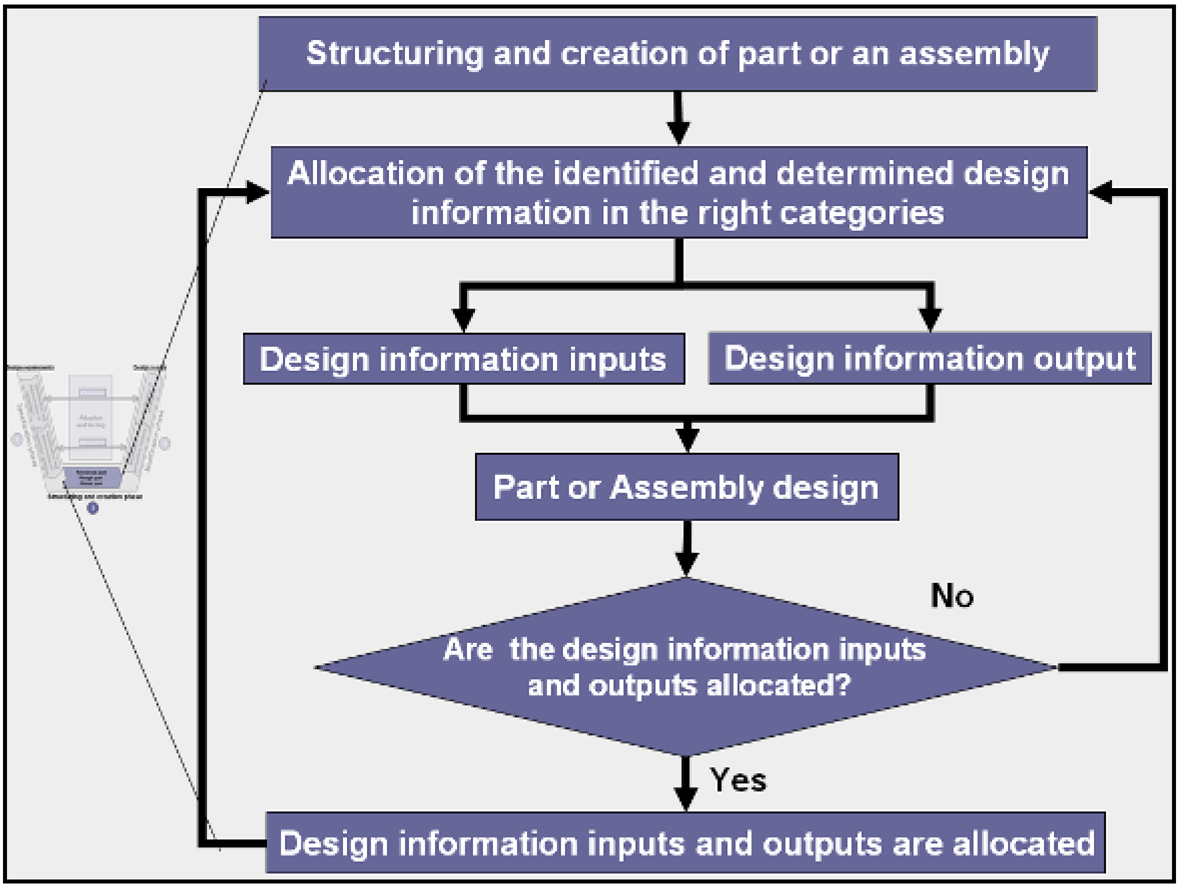


Figure 44: Structuring of PA design information inputs and outputs

The pre-defined structures of the approach are a PA Assembly Structure (PAAS) and a PA Part Structure (PAPS). The PAAS is based on associative relationships between different CAD parts which represent the hierarchical structure of the designed PA assemblies.

6.6.1 PAAS approach

The PAAS is hierarchically ordered and contains three parts connected by means of associative relationships. These three parts are 1) reference model; 2) rough part; 3) finished part. The idea behind the three parts is that the designer can work from the conceptual design stage to the more detailed stages of the design process with PA CAD systems. Furthermore the design process participants are able to access the different parts created in PAAS so that a concurrent and simultaneous engineering environment can be enabled. For example manufacturing engineers who are interested in the rough-part created can capture their required parametric model information. Furthermore, based on the rough part, the machining process steps can be created by the difference between the rough and finished parts. The first part of the PAAS defines the associative elements and the architecture of the conceptual design elements and contains all the technical specifications of the CAD component as well as boundary geometry (this are geometries which are in the surrounding of the created PA components and geometry) and constraints.

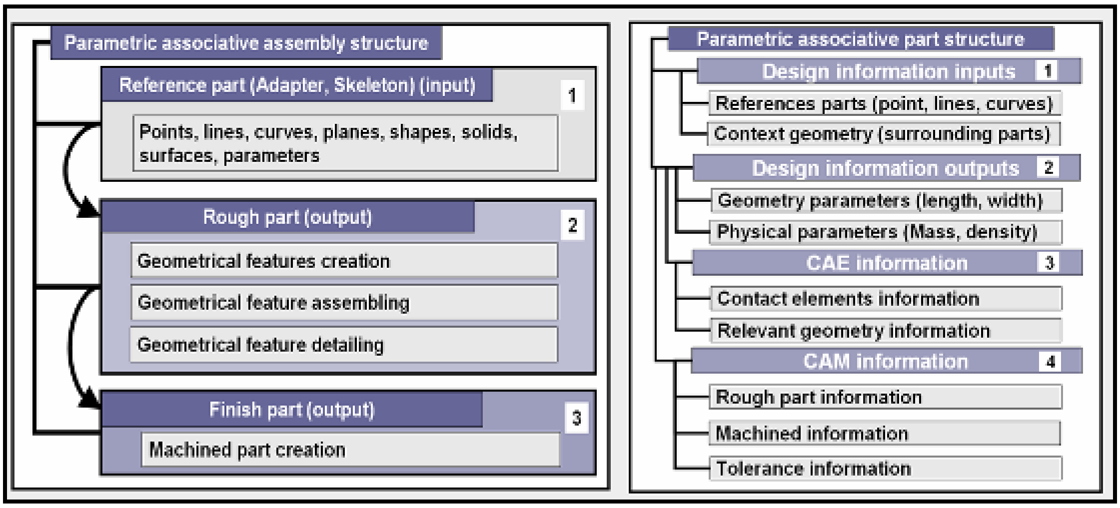


Figure 45: Structuring of design information inputs and outputs at part and assembly level

The architecture is a set of logical and parametric features of an object or system that can be used to build the CAD model. Furthermore the reference model contains the input information which describes the base-elements of the CAD component. These base-elements are axes, coordinate systems, lines, curves, surfaces, solid geometry, parameters, styling geometry and contextual geometry such as standard-, purchased- and carry-over parts. Furthermore the design engineers are able to modify the designed components by only changing the base geometry and parameters in the associative part. The second part of the PAAS is the design process of the rough part. The rough part contains the basic geometrical feature information and the assembly of the geometrical features by means of Boolean operations (e.g. union, trim etc.). The final design step of the rough part is the creation of detailed information like the filleting and chamfering information for the CAD components. The third part of the PAAS contains the finished part. The finished part contains all the machining information of the CAD component. At the part level there exists also a pre-defined structure which is important for the implementation of the identified parameters and associative relationships.

6.6.2 PAPS approach

The next predefined structure is the PAPS which are divided in 4 different parts. These four different parts should help to structure the identified parameters which are necessary for down-stream processes and for the CAD design participants. The first part of the PAPS contains the input information necessary to design the CAD components and describes the base geometry. The input information is associative geometry such as points, lines, curves and contextual geometry which describes the geometrical surroundings at the part level. The second part of PAPS describes the area where the geometry should be created and maintains the main result of the design stage the embodiment area. The third and the fourth parts of PAPS are created to enable the exchange of information necessary for the down-stream processes. In this case these two areas are the CAE engineering and CAM engineering process partners. Figure 45 shows the PAAS and PAPS approach

Figure 46 represents an example of structuring stages of the piston pin starting with the definition of the reference model which contains the base geometry such as position, external diameter and horizontal axis of the piston pin. Based on the reference model and by means of an associative connection the next stage is the design of the geometrical rough part which contains basic features, Boolean assembly of the created features and the geometrical detail information (i.e. rounding and edge trimming). The third stage contains the finish part of the piston pin which is the difference between the rough part and the machine part elements (i.e. turning and boring).

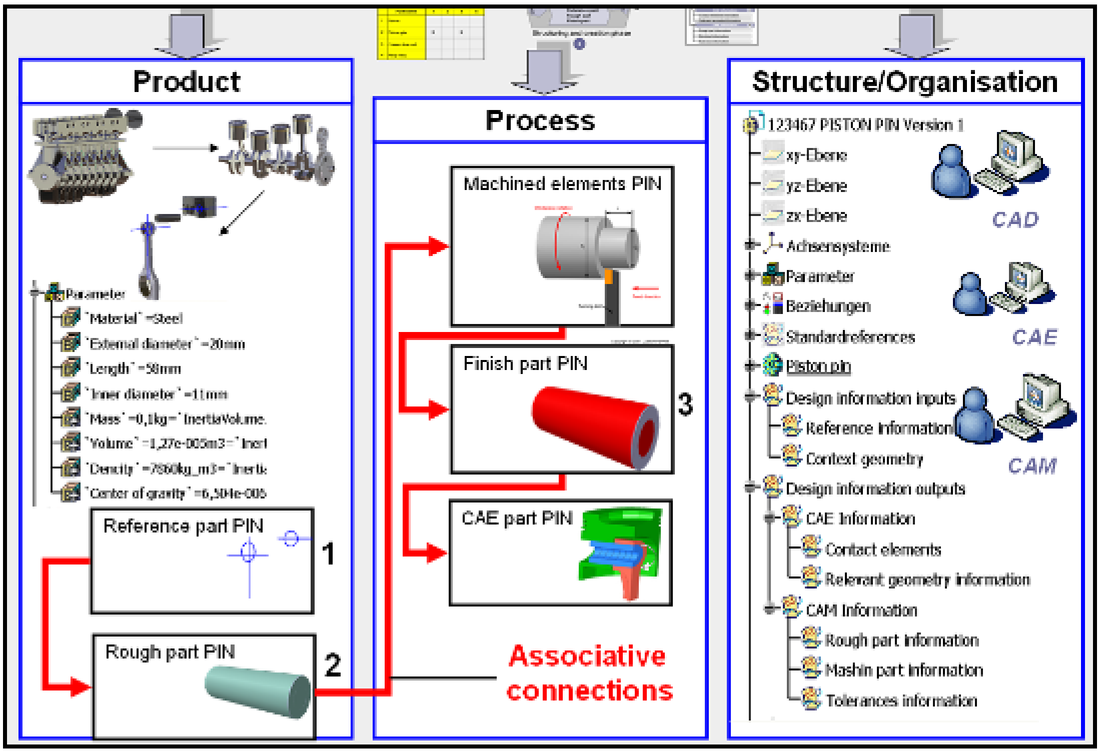


Figure 46: Final result of the structuring of information inputs and outputs of the pin

For the intake valve assembly creating the relevant parameters and associative relationships are shown in Figure 47.

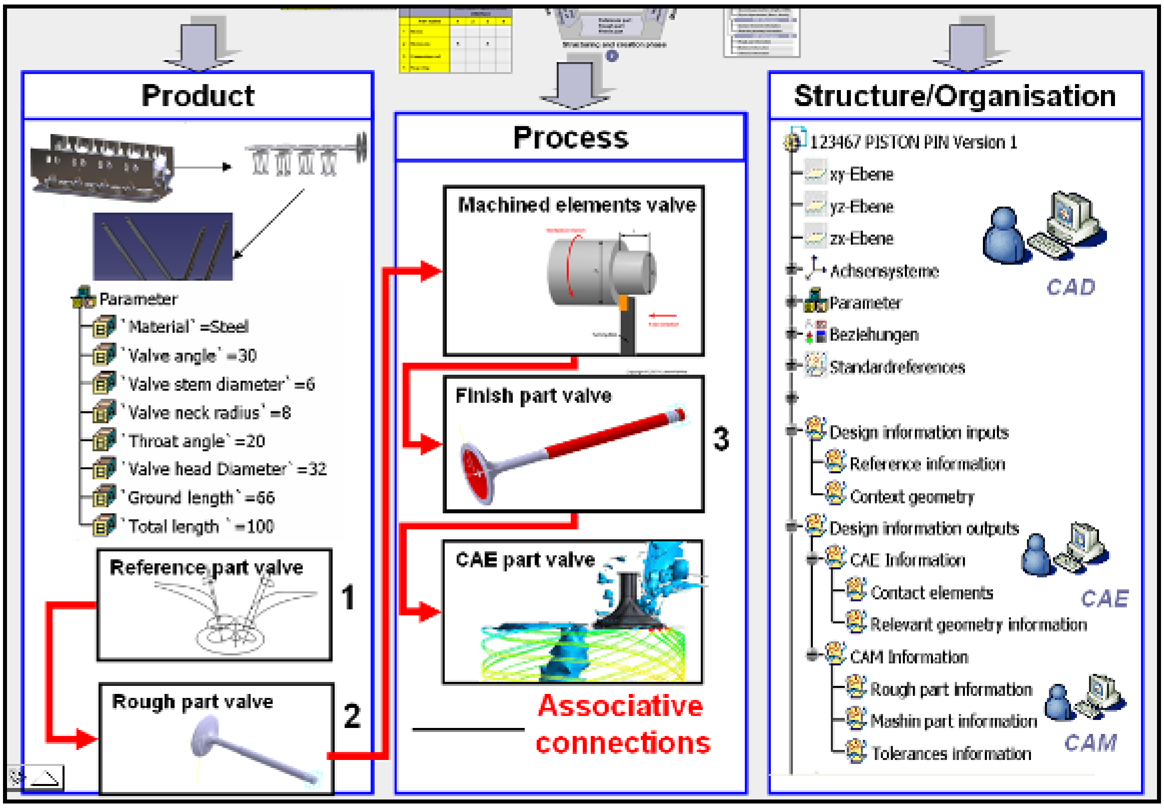


Figure 47: Final result of the structuring of design inputs and outputs of the valve

6.7 Phase 3: Modification phase of the PA CAD design

The final phase of the integrated approach is the modification (as required) of the parameters and associative relationships and helps test and evaluate the created parameters and relationships. The most important point during the modification phase is to check a) the consistency of the created parameters to ensure they can be changed and the CAD parts and assemblies can be regenerated without failures and b) the consistency of the created PA relationships between the geometrical entities and objects to ensure that in case of geometrical changes the associative relationships still work. Related to the example PA piston and piston pin it was possible to change the created geometries and associative relationships. That means that by means of the clear structure and predefined component the modification of the parts were easier. This was also the feedback of the designers who applied the method. Furthermore by means of the modification of the parameters and associative relationships it was possible to check the robustness of the created CAD components.

6.8 Application of the PARAMASS approach in other Domains

During the application of the PARAMASS approach it was possible to observe that there was an interest from other Departments like Body in White to apply this approach. Therefore the author tried to discuss the possibility of the PARAMASS application in other Domains inside the automotive company. It was possible to select CAD components from Body in White and try to transfer the PARAMASS approach for creating the Body in Whit CAD components. During the application of the PARAMASS approach following points were observed:

Related to the PARAMASS approach and its Phases it was possible to apply the first Phase which is the specification phase without any greater problems. By means of the generic nature of the ASM and PSM approach it was possible to create the parameter and associative relationships of the Body in White component. It was possible to observe that a transformation of the ASM and PSM approach was possible. Furthermore the advantages which were available during the application of the PARAMASS approach for creating power train CAD components were also here available.

During the application of the second phase of the PARAMASS approach (creation and modelling phase) it was possible to observe that the developed PAPS and PAAS approach were limited during the application. The reason therefore is that CAD part power train development has another manufacturing process than CAD parts in Body in White. That means that in manufacturing CAD components in power train most of the part are separated in rough parts and finishes parts. In Body in White other aspects in manufacturing are important like deep drawing direction of position of the point for welding the components. But it was possible to observe the base idea to bring the required information in Body in White design in such a standard structure was also welcomed. This aspect could be a further contribution of a potential future works. This means the application of the PARAMSS approach in other section and domains. It would be quite interesting to see if the developed PARAMASS approach does also work in other domains.

6.9 Conclusion

The need for a new method for the application of PA CAD systems in industrial environments has been identified in earlier chapters of this thesis. Based on the results of the literature survey and the results of the Descriptive study I it was possible to identify the most important issues related to the definition, identification and determination of the created parameters and associative relationships. In this chapter an integrated approach which accompanies the designer from the concept to the detail stages of the CAD design process with PA systems has been identified. The developed PARAMASS approach contains three different phases which are the 1) specification phase, 2) structuring and creation phase and 3) the modification phase. All of these developed phased are based on the results of the literature survey and the Descriptive Study I.

The most important phase during the design process with PA design is the specification phase (Phase I) which is the basis of the further design phases. During the specification phase the designer gets an understanding of what to do next and what are the important parameters and associative relationships. The PSM and ASM approaches have been presented as methods to identify, determine and document the relevant parameters and associative relationships between the geometrical entities. Furthermore it was possible to learn that designers in an industrial context need approaches which can be easily understand and applied during their daily work. By means of using the PSM and ASM approach is was possible to observe that designers were familiar with such simple representation of information and it was not necessary to explain them the idea of how to deal with the developed approach. Beside this the designers mentioned that the approach helped them to understand the complex relationships between their parameters and the associative relationships. By using “spread sheets” for collecting the information based on ASM and PSM approach designers were also able to share their information with other process partners who need the information from the design departments. In this way the other process partners were able to pick up the related information for their processes. Designers mentioned that by means of the PSM and ASM approach there are able to document and to catch the relevant information to their parameters and associative relationships. Beside of all these aspects it can also be elaborated that the PSM and the ASM approach have a certain kind of generic nature and can be applied also in other domains like aerospace industry. This aspect can be a potential contribution of further future works which will be addressed in Chapter Nine.

The structuring and creation phase (Phase II) of PA design has also been considered. By means of a predefined structure layout for the created PA parts and assemblies it is possible to increase the design transparency, to increase the reusability, to standardize the structure, to define a hierarchical order of the different design information inputs and outputs and to integrate clustered and classified parameters and associative relationships in the CAD parts and assemblies. The structuring approaches presented were based on the PAAS and PAPS models. By the application of the structuring and creation phase it was possible to observe that this approaches (PAAS and PAPS) helped to implement a kind of "standardised" structure of the PA CAD parts and assemblies. All the design departments get a common understanding about the existing structure of the CAD components. Furthermore designers and their process partners exactly knew where the required information could be found. It was also possible to learn that such a well defined and standardised structure helps to exchange the required parameters and associative relationships with the suppliers who worked with the automotive company.

The final step (Phase III) which was the modification phase helped designers to check if the defined, created and designed parameters and associative relationships work.

The next chapter will present the implementation and evaluation of the new developed approach PARAMASS.

7 Descriptive Study II: Implementation and evaluation of the PA approach

This chapter will define the important aspects what should be considered during the implementation of the developed PARAMASS approach. After a general introduction the next section will present different method integration approaches which have been developed and used in different contexts. In the following section one of the approaches presented is selected and applied for the integration of the developed PA approach.

A series of research papers and works was involved with the implementation and integration of systematic design methods [STREICH, 1997], [BESKOW, 1998], [TAMIMI, 1998], [STETTER, 2000]. In all of the works it was mentioned that during the implementation of a method the change management process of the participants should be considered. Streich describes [STREICH, 1997], that the starting point is the question if the competence of the actors who are responsible for the process of the change management can be clearly perceived. Besides, the following important dimensions (competence fields) have to be considered in particular:

- Ability to do something, change of ability;
- Willingness to do something, change of readiness;
- Possibility to do something, change possibility;

In a well-balanced mix of these three competence fields the perceived ability in different situations can be raised [STREICH, 1997]. The basis of the action shows an innovative and changing plan which questions the established approach at the procedural and behavioural levels [STREICH, 1997]. New plans of change management require, apart from new contents, new methods and behaviour patterns. Figure 48 shows the different stages of the change process. This “change management graph” shows two dimensions: the perceived competence and the period of time. The phases shown within the graph (from the shock up to integration) differ between people. But for effective learning processes (in this case the integration of a new design method) the different stages have to pass quickly [STREICH, 1997].

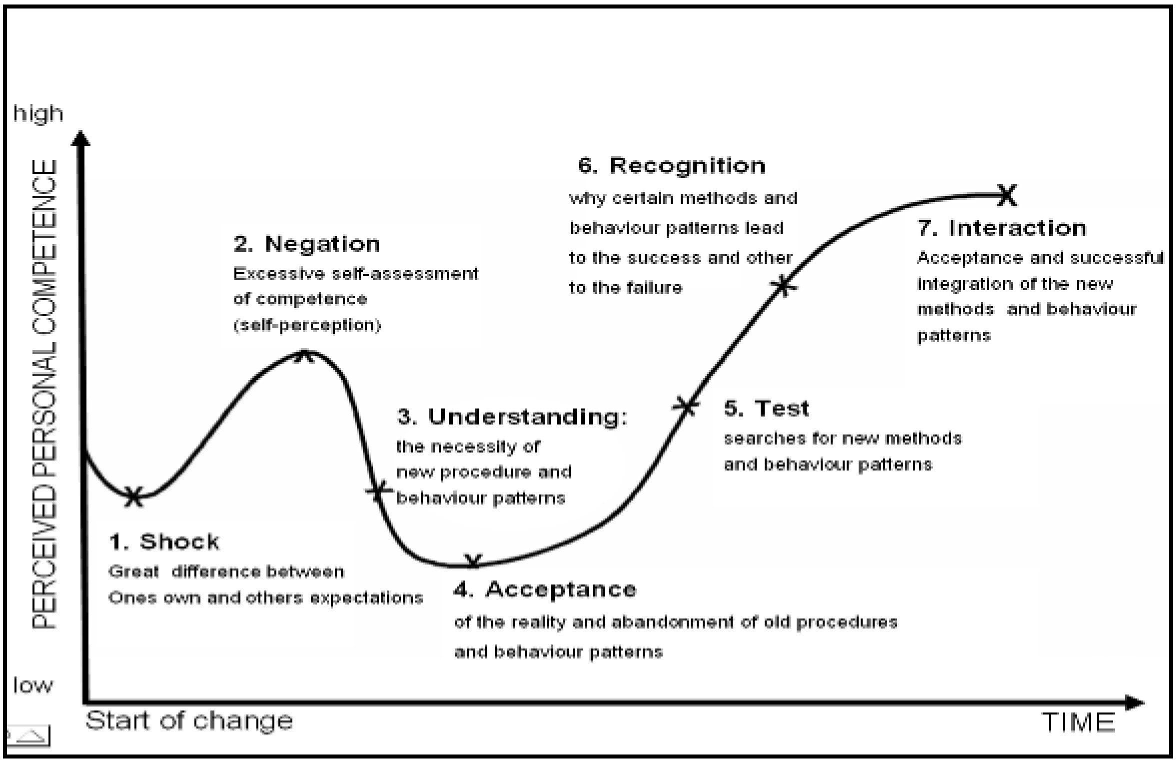


Figure 48: Single phases of the change management [STREICH, 1997]

The reason for considering the change management graph is that the implementation of a new design method can also be seen as a "changing" of the procedures and methods of different designers. This is a very important aspect during the implementation of new approaches. There are different procedures of implementing new design methods. According to Stetter [STETTER, 2000] activities that represent the adoption of a new method is the driving force of design methods. This means that one of the most important issues is the association and connection of the designers with the implementation process. This process comprises the introduction, anchoring and the improvement of the new methods. Several significant aspects of the implementation itself have to be taken into consideration to guarantee successful method implementation [STETTER, 2000]. Basically, the performance of new design methods demands the accomplishment of an implementation strategy and the monitoring and the adaptation of the selected methods.

Another very important point is to prevent designers from developing a "resistance" to the intended change in the design process. To avoid such resistances the author used the resistance pyramid of method implementation created by Beskow [BESKOW, 1999], which describes characteristic patterns of resistance demonstrated by workers during the implementation of methods (Figure 49).

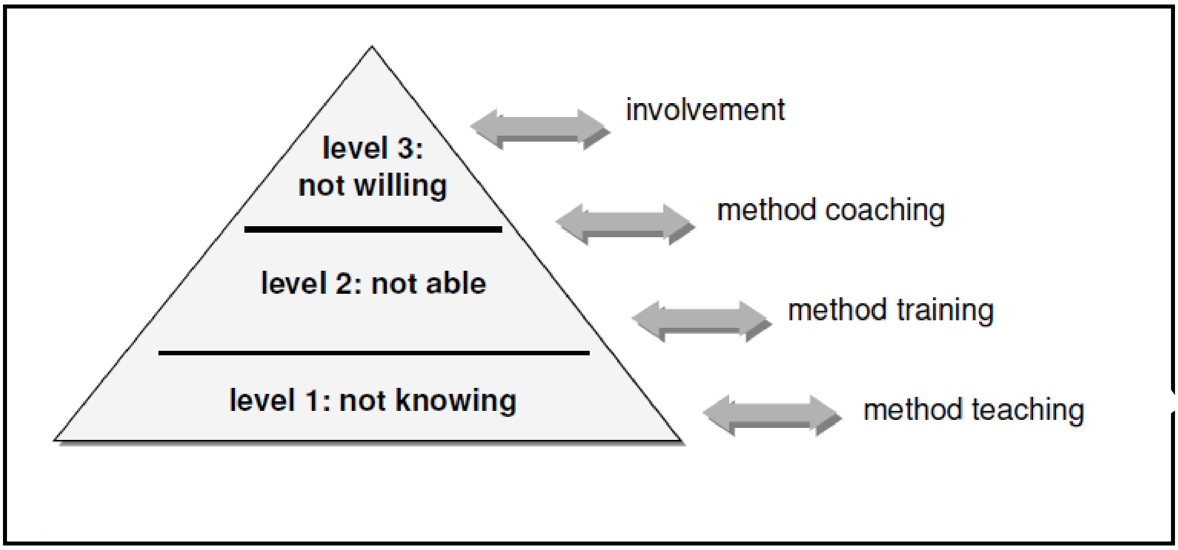


Figure 49: Resistance pyramid [BESKOW, 1999]

The resistance pyramid of Beskow [BESKOW, 1999] includes three different steps and levels. These levels are named as “not knowing”, “not able” and “not willing”. According to Tamimi [TAMIMI, 1998] changing designers’ “resistance” is one of the key issues and also very important for the implementation of new methods. He also defined strategies of how to counter people’s resistance. The levels ‘not knowing’ and ‘not able’ can be attacked by means of teaching the new method, training the new method and coaching the designers during the application of the new method [TAMIMI, 1998]. The best way to avoid the highest level of the resistance ‘not willing’ is to win such designers’ support for the method development, which means to integrate designers into the implementation process.

7.1 Presentation of method integration approaches

There are different approaches which have been developed for the implementation of methods in different domains. This part of the work will address some relevant works related to the implementation of methods in general. A basic model of method implementation is presented by Beskow [BESKOW, 1999]. In this generalised model, a change process and likewise the implementation process is assumed to consist of three phases: planning, implementation, and evaluation (Figure 50). The approach according to Beskow can be evaluated as one of the less complex models of the method implementation process. But as this approach defines a very high level description of the method implementation process that means that sub steps which are necessary, i.e. to plan, implement and evaluate the developed approach are not considered. Therefore the general description of the method implementation phases are valid but more detailed information how to plan the required activities of method implementation process would be more helpful.

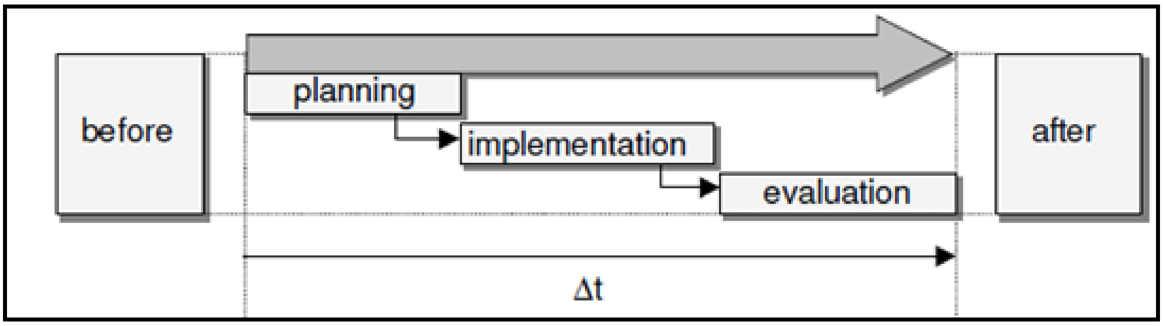


Figure 50: Generalised model of a change process [BESKOW et al. 1999]

Another, quite different model of method implementation can be found in Dobberkau [DOBBERKAU, 1999]. This model is aimed at the implementation of TQM in small and medium sized enterprises and actually consists of three models: the method model, the environment model, and the method life-cycle (Figure 51).

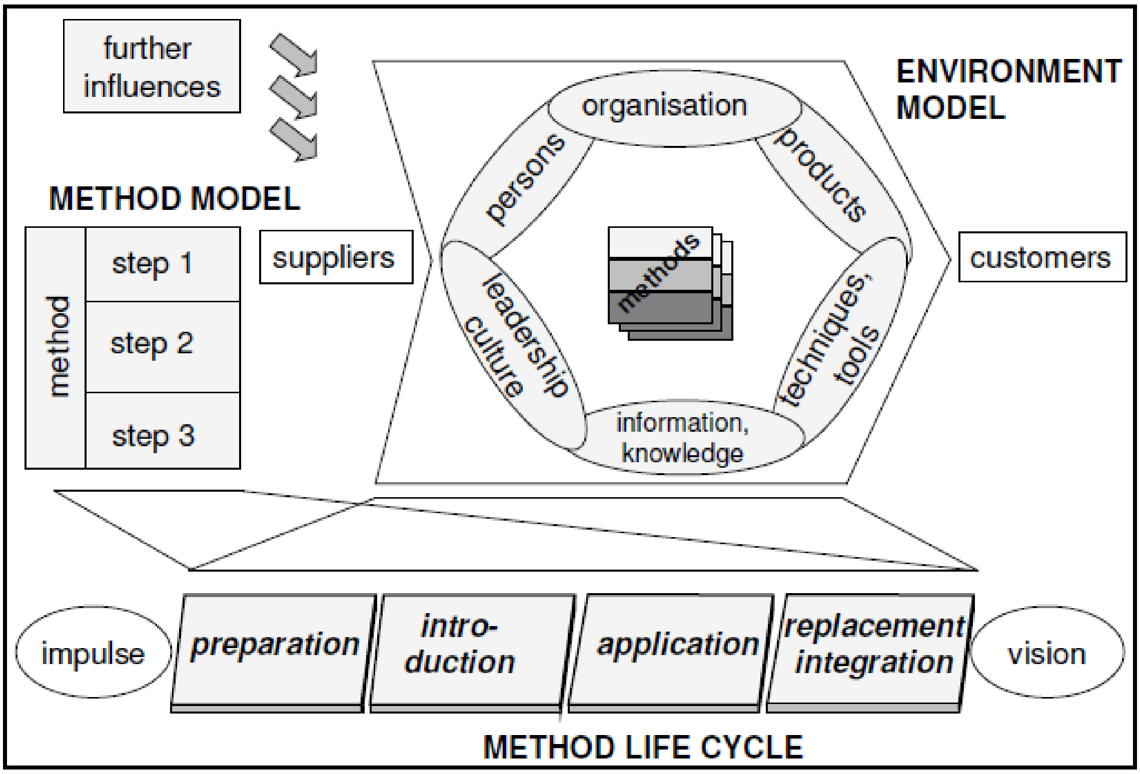


Figure 51: Models for handling of methods [DOBBERKAU, 1999]

The model lists methods as formal directives consisting of steps to be carried out. The environment model contains the elements of the environment to which a method should be adapted. The method lifecycle shows the phases that have to be expected when establishing a method (Figure 52).

Another complex model that is also aimed at implementing Concurrent Engineering (CE) was developed by Driva [DRIVA/PAWAR, 2001]. This model, which is referred to a generic framework, can be characterised as a cyclic approach. In particular, the phases 'develop a strategy' and 'create the culture' underline the more strategic approach behind this model. Furthermore there are 7 different steps which make this approach less suitable for the application.

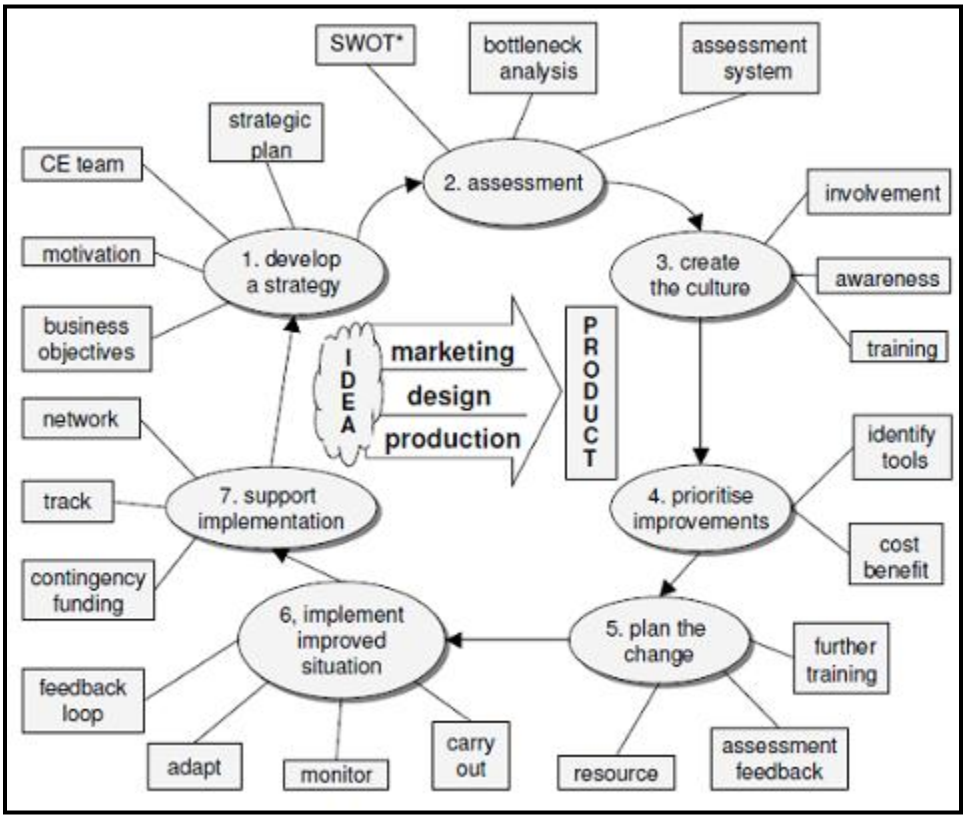


Figure 52: Generic framework for implementing concurrent engineering [DRIVA, 1997]

Stetter [STETTER, 2002] developed a five layer preliminary model of method implementation which summarizes activities in a method implementation approach that exhibit a strong interrelation in terms of content, i.e. the activities in one layer are concerned with similar aspects of the method implementation process (see Figure 53). The chosen distinction between the layers is based on the comparison of the presented models of method implementation, their accompanying literature, and insights gained in the case study. The course of action can start at any layer, but it must include activities on every layer in order to increase the potential of a method implementation to be successful. In the observed case, the course of action approach changed between the layers several times.

The model was developed as a preliminary means to encourage the discussion of method implementation. In the author's opinion, the presented model is of value for someone initiating or participating in a method implementation process because, even if it does not propose a course of action, it still may be used for identifying the logical stages of an implementation process. Because the approach according to Stetter has fewer phases and steps it is very helpful to apply this for the developed PA approach. Furthermore the different phases suggest also different sub phases which can be adopted in any level of the method implementation process. The next section will explain the planning and implementation phase of the developed PA approach.

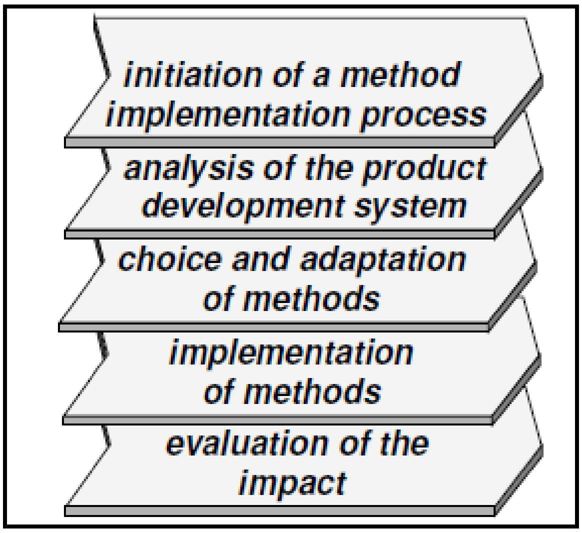


Figure 53: Five-layer model of method implementation according to Stetter

7.2 Planning the implementation of PARAMASS

The implementation of methods and the factors which should be considered has been addressed by a number of studies. It is quite important to create a plan for determination of tasks and actions required to realize the method implementation [USHER, 1996]. According to Berndes [BERNDES, 1998] "the starting point of the method implementation is the planning of activities which contains the course of action, like the sequence and intensity in which certain activities are performed, the persons who perform them, and what resources will be available". Furthermore the planning of a method implementation process can be compared with the planning of a product development process. A large number of methods for planning are presented in the literature. From the viewpoint of planning, there is not much difference between a method implementation process and other determined processes, for example, product development. According to

Lindemann [LINDEMANN, 1999] the choice of the planning system to apply should therefore be based on the capabilities and needs of the respective company. Furthermore it is important to remember that the systems need to be simple in order to remain transparent for the participants. According to Pinosz [PINOSZ, 1997] there are three different introduction strategies which are:

- All-at-once: a method can be introduced by changing the whole system overnight.
- Pilot application: a method can be applied first in a pilot application of limited scope and then the scope can be expanded if the method has been proven to be useful and its faults have been corrected.
- Gradual approach: selected aspects, for example, rather simple accompanying tools of a method can be applied first, for example, in a particular department, and the other aspects can be introduced later in a stepwise procedure, if the selected aspects were accepted by the designers.

The first approach which is the ‘all-at-once’ approach will usually be too risky since methods and tools cannot be tested in advance under realistic conditions. Pinosz [PINOSZ, 1997] stated that if a method does not offer the full required functionality, it will quickly become a burden. Therefore, a rigorous testing phase of the developed PA approach was planned and expected. This aspect can also be captured from different literature and publications [DANNER/RESKE, 1999], [WEBER, 1999], [LETTICE, 1998], [SELLGREN/HAKELIUS 1996]. Related to the introduction of the developed PA approach the “pilot application” approach was the most suitable. By means of this approach it was possible:

- To verify the realisation of the major objectives. That means to clarify the possible application times and also the PA CAD design examples which should be applied by the CAD designers.
- To enhance the qualification of the employees by means of ‘training on the job’. It was possible to observe that for CAD designers it is more comfortable to apply the new learned method on their daily task.
- To provide CAD designers and other participants like CAE and CAM engineers in the rest of the organisation with real demonstrations.
- To intensively explore and highlight the needs of the CAD designers.

- To assist the setting of realistic schedules.

The target of a “pilot project” was a precondition to be able to inform all the CAD designers and the design process participants like CAE and CAM engineers in detail. The pilot project for the introduction and implementation of the PARAMASS was planned for eight months. According to Usher [USHER, 1996] the main purposes of the pilot application are:

- A project should be selected that is large enough to include a good sampling of typical functions but not so large that the success of the project is jeopardised.
- A project should be selected that will require resource commitment in terms of cost, time and personnel without overextending these resources.
- The product to be developed in the project should exhibit problems in terms of time, cost or quality in order to increase the likelihood of improvements.
- It has to be understood that this project is to be used as a training ground for management and team members.

The integration of a “gradual approach” was considered not to be suitable. The most important reason for this was that the managers in the CAD departments were waiting for already created and finished results at a time when even the collection of the data in the analysis of the product development system was not completed. Furthermore before starting to integrate the PA approach it would be very interesting to get further information about the experiences of the CAD designers with method implementation. From the viewpoint of the author this aspect is one of the important ones because by means of getting information about designers’ experiences it was possible to create a plan of how to tackle possible challenges during the PA approach implementation phase. In addition it was possible to create a fitted and suited introduction and implementation plan for the participants. Another aspect was that you cannot to make the same “mistakes” carried out have been done in the past during the implementation of methods in the CAD departments. For getting information about CAD designers’ experiences with method integration processes a questionnaire was designed to collect the problems and challenges of the CAD designer during the implementation of a methodology. The most important results and problems of the designers during the implementation of methods are presented here:

- Lack of involvement of the CAD designers about the planned activities; 96% of the respondents mentioned that during the method planning and implementation process they are not sufficiently involved in activities which are necessary to implement the methods. Furthermore they also mentioned that managers tend to plan all the activities without any consideration of their needs and requirements. The CAD designers also mentioned that they are willing to learn and apply methods which help them to work in a better way but a "top down" approach of integration of methods by managers leads to a certain degree of frustration for the designers.

- Lack of support for CAD designers during the application of methods; 92% of the respondents mentioned that in most of the cases there is a lack of support during the learning and application phase of new methods. Therefore it is quite important that during the initial phase of the method integration CAD coaches and external support are available for the designers. Furthermore the CAD designers also stated that the CAD coaches and support people should be located in the same area as the CAD designers. In this case it is ensured that in case of possible questions and problems during the learning and implementation process of the developed methods problems and difficulties can be tackled faster and immediately. The designers also feel secure that in case of a problem someone is there who is able to help them.
- Lack of the targets for the planned activities and the method; 86% of the respondents stated that in most of the cases the target of the activities and new methods are not clear or well explained. That means that there is less information about why the CAD designers should learn a method. In case of the integration of the developed PARAMASS by means of the presentation of the results from Descriptive Study I (in which all the designers were involved) it was possible to show the weaknesses and challenges of the created PA parts and assemblies. Furthermore by means of investigation of existing CAD parts it was possible to demonstrate the possible challenges and improvements during the modelling process.
- Lack of time resources which are necessary to implement the method; 91% of the CAD designers mentioned that during the implementation of methods the time boundaries are not considered. That means that the time which is selected to implement the method is in most of the cases not suitable. The designers also mentioned that if the people who are responsible for the integration of methods would ask and involve them in choosing possible time slots it would be more comfortable for the designers to plan the implementation in their daily tasks. Related to CAD designers this aspect was one of the important ones because in the

design process there are several deadlines which are important for them. For example there is a deadline about the release process of the created CAD parts and assemblies. At this time it was not very suitable to implement the developed PA method.

- Lack of having voice about possible changes and improvements of methods; many of the designers mentioned that it is very helpful if they would have the possibility to give a statement about possible improvements and changes of the methods. That means that in most of the cases it their ideas about improvements are not sufficiently considered.
- Lack of communication about the planned activities. The achievements and the next steps and activities during the method implementation phase should be communicated to all the participants. Furthermore an "open" communication about problems helps to get more inputs about the weaknesses of methods which can be used for further improvements.
- Lack of financial resources necessary to implement the method. This aspect is more related to the management level. The designers mentioned that in the initial phases of the method implementation there is a certain support necessary and in most of the cases there is no money planned to support the designers. Most of the designers have to learn methods beside their daily work and the time is missing to learn these approaches without any support.

Other problems during the method implementation process have been identified by other researchers in other areas [STETTER, 2000], [BESKOW, 1999], [REETZ, 1995]:

- The competence to implement methods was found to be distributed over the company. Staff departments seemingly did not know the processes and especially the diversity of the processes. The line departments did not seem to have the qualifications, the competence, and the authority to implement methods or tools.
- The products to be developed have become more and more complex. Therefore the need for co-ordination has increased and designers believed that they are already spending most of their time in inefficient meetings and were declining anything that would lead to a stronger integration, because it could result in a need for even more time to be invested in co-ordination.
- Many of the designers had already participated in failed method implementation approaches and were therefore eager not to invest additional time in projects they considered doomed for failure anyway.

- The researchers got the impression that some designers tried to protect their competence, their authority and especially their status by means of withholding information or not sharing the methods they developed for themselves.
- The designers frequently complained about too many required documents because of the ISO 9000 certification and were not willing to document more.
- The lack of a powerful internal intercessor in the introduction phase caused immense problems.
- It was nearly impossible to inform all designers in the preliminary stages due to time constraints.

The identified aspects about the limitations and problems which are important for the integration and implementation of the developed PA approach were considered during the implementation phase. The next section will define the planning and implementation phase of the developed approach.

7.3 Targets, issues and challenges of the pilot project

This section of the thesis will explain the organisational aspects and the participants who were involved in the pilot project. Derived from the issues which have been explained in the last section it was very important to plan a strategy to be able to implement the PARAMASS in a successful way. Moreover the biggest challenge was how it would be possible to consider the problems and gaps which have been identified by carrying out the questionnaires, interviews and literature survey. First it is very important to define the targets of the pilot project. These were:

- The integration of the developed PA method during the design process with PA CAD systems.
- The definition of a pilot project and its members to integrate the developed PA approach.
- The definition of the time schedule for the PA approach implementation.
- The presentation of the results of the questionnaire which have been carried out in the past.
- The demonstration of the methodological necessity and fields of action during the design process with PA CAD systems.

- The explanation of the most important issues which have been identified during the analysis phase.
- The transformation and implementation (teaching, learning and training), introduction and application of the developed PA method.

Defining the targets of the planned activities is very important. Especially in a real design environment such as the automotive industry it is quite important to be able to convince the very busy CAD designers of the necessity for change. Related to the definition of the targets of the developed PA approach it was possible to demonstrate the issues and problems which have been identified during the Descriptive Study I. In this case it was possible to bring the real evidence that there are serious problems related to the created PA CAD part and assemblies. The simple target was to say that the department is going to improve the quality of the created CAD components. Furthermore during the target definition it is very important to give the designers the “feeling” that the activities which are planned should “help” them to create better CAD components and to work in a better way with such complex CAD systems. Another important aspect during the definition of the targets is to get the full commitment of the designers. In some cases it is also very important to sign an agreement with the involved designer about the target of the developed PA approach. But this aspect was also very different from department to department and also for single designers (it was more a question of the characteristic of the designers). The aim was to try to give the participants and the designers a vision about the planned targets and activities.

The next aspect which should be considered is the question of **who** is involved in the implementation of the PA design approach. During the determination of people who are involved in the planned pilot project and activities it was quite important to consider the issues raised by the designers about the problems and negative experiences in the past related to method implementation processes like involvement, support, required resources, communication and other important issues. Furthermore it should also be considered how the organization of the people who are involved in the pilot project can be created by considering the above mentioned limitations and requirements. The participants who are involved in the development and implementation of the developed PA approach will be explained in Figure 54.

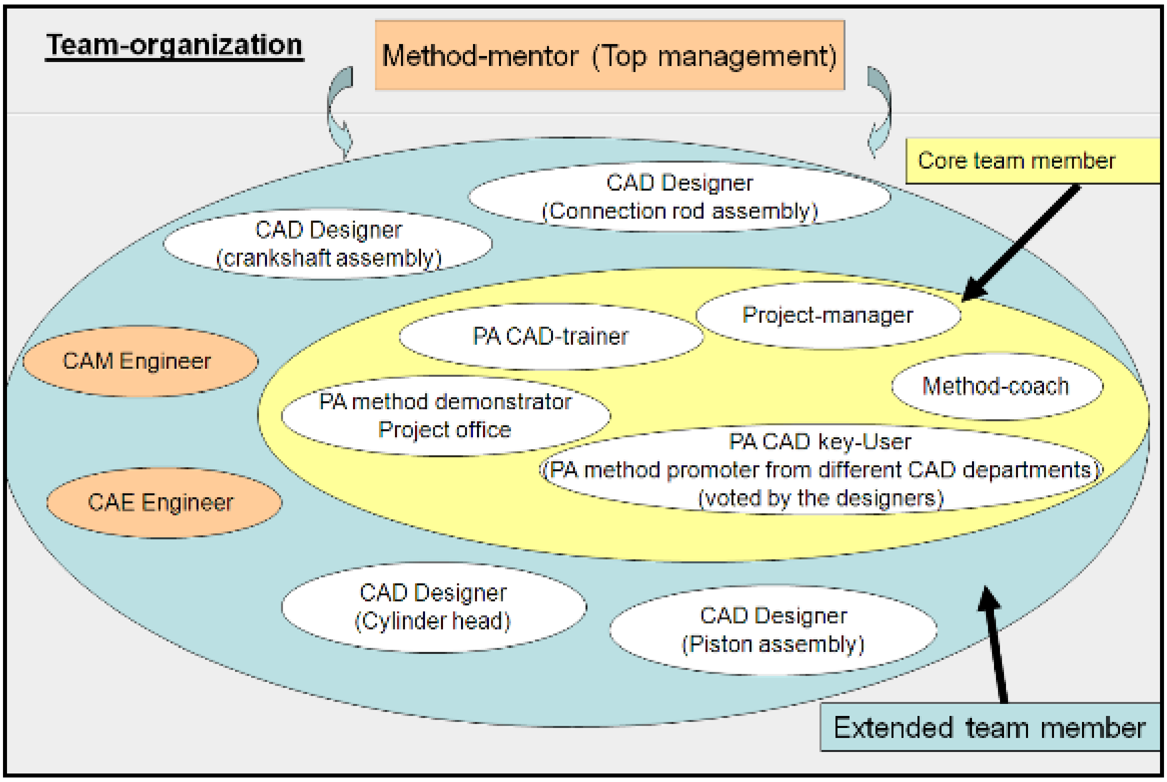


Figure 54: Organisation of the pilot project during the implementation phase

Participants for the pilot project were divided into two different teams. The first included the core team member and the second the extended team members. The core team was responsible for the technical issues of the PARAMASS. The participants of the core team were the project manager, PA CAD coaches, method coach, the demonstrator and some experienced designers sent by different design departments. Furthermore it was ensured that each of these members had their purpose and responsibility. This core team was organized in a way to be able to tackle the problems which have been identified before. Furthermore based on the factors which make implementation difficult the selected members should help to reduce the implementation risks and challenges. Now the next sections explain the strategy of tackling difficulties and challenges during the implementation of methods.

7.3.1 Tackling the involvement problem

The significant meaning of involving employees in a change process is addressed in several articles [HARTMANN, 1998], [AKADEMIE, 1999]. The strategy for organisational change that requires a high level of involvement of the designers and participants is also described as a 'participative approach'. The characteristic of such an approach is the "active role" of the employees [HARTMANN, 1998]. By means of the participation of the employees it was possible to observe that the acceptance of the proposed PA approach and planning activities increased. Furthermore the CAD designers committed themselves to the planned activities and changes. In this way the changes were planned and initiated by the CAD designers and design departments. In addition each of the CAD design departments sent their “key-designer” (normally people from departments who have certain experience of design tasks and also the in house processes) to give important inputs for the requirements of the PARAMASS. The key-designers can also be considered as a kind of “PA method ambassador” for their departments. They act as a kind of “interface” between the technical development team of the PA approach and the CAD design departments. Furthermore they are responsible for the coordination of the discussed PARAMASS contents and issues with their internal colleagues and design departments. By means of implementing the “key designers” as core team members it was possible to integrate the issues and requirements of several CAD design departments. Therefore the author was able to observe a very positive feedback about the planned and accomplished activities inside the team. Further general positive aspects of employee involvement are [HARTMANN, 1998]:

- Enhancing the transparency of the implementation process: employees know the process they design.
- Integrating know-how of the employees: knowledge, for example, about routines which are not documented, which can be used in the implementation.
- Simultaneous qualification: capabilities such as team building are taught during the participative development of the implementation process.
- Improved information flow: information can be exchanged directly between the employees.
- Enhanced flexibility and stability of the implementation process: employees are empowered to react in an unexpected situation independently.

7.3.2 Tackling the support problem

For tackling the support problem which has been mentioned by the CAD designers it was possible to observe that in case of integration of PA approaches there are two different kinds of support necessary. The first support is related to the PA CAD system itself. That means that there are issues which should be clarified from the PA CAD system side like application and meaning of the different functions which are offered by the CAD system. Therefore a PA CAD system expert was engaged in the pilot project to clarify problems and challenges caused by the CAD systems. The expert was also responsible to support the designers in case of problems with the PA CAD system. The second support necessary was the support from the methodological side. That means that in this case someone was necessary to support the designers about questions which are related to the PA method itself. Furthermore the method coach and the PA CAD system expert were located in the same place as the designers. Therefore it was possible to have a very quick response to tackle problems caused during the implementation phase. In general the tasks of the PA CAD system and method expert can be defined as follows:

- To help designers to reflect the learned PA approach and its different steps.
- To support designers in the preliminary stages of the method application.
- To support designers to solve a special design problem with the method.
- To collect and to reflect the weakness of the new method.

Beside the support of PA CAD and method coaches there was also a project manager involved. The project manager was the central person in the project planning and activities. According to Madauss [MADAUSS, 1994] the project manager is responsible for ensuring that both the technical and economical objectives of a project are achieved. Furthermore the project manager should have the authority and the competence to:

- Plan, direct and control the technical tasks.
- Choose contractors and suppliers.
- Plan, release and control project costs.
- Plan and control the scheduling.
- Implement an effective and efficient project organisation.
- Choose the key personnel.
- To be the interface between the development team and the management.

The members of the project are normally assigned by the project manager. The extended team of the implementation team should be cross-functional or interdisciplinary. According to Steinmetz [STEINMETZ, 1993] the following members should be implemented in a task force:

- An external consultant.
- An expert in data processing.
- An organisation expert.

The above mentioned aspect can help to support designers in their administrative tasks and issues. That means that by means of integrating such external support it is possible that the designers will have a full concentration to the method implementation. But it is also very important that such an organisation is only possible in big companies where a lot of designers have to learn or to apply a new PA CAD system or method.

7.3.3 Tackling the resource and support problems of management

According to Prasad [PRASAD, 1996] there are two different solution approaches - "top-down" and "bottom-up" - to organise and implement a method. The characteristics of these two different approaches are [PRASAD, 1996]:

- In a top-down approach, the management of the company appoints a team of experts from various disciplines and empowers them to come up with a vision of what the future product development system will look like and to select methods that realize this vision.
- In a bottom-up approach, the 'to-be' process is evolved from the 'as-is' process as opposed to being defined *a priori*.

In a real industrial context it is quite difficult to separate both approaches, and the implementation will often be a mix of both presented approaches. Prasad [PRASAD, 1996] also recommends the application of a combination of "bottom-up" and "top-down" approaches. It is also possible to observe that in many cases a certain "management attention" is necessary to demonstrate the important of the current project and its results. This aspect is also mentioned in other projects which were related to the implementation of tools. According to Beskow [BESKOW, 1998] management support plays an important role in tool implementation. Furthermore without consistent top management support, internal politics may hinder implementation processes. Usher identified that a company must ensure that every level of management is both committed to and involved in the transition [USHER, 1996]. If the top management is engaged in the implementation process the integration of a tool or method seems to be very important. It will also demonstrate that there is a high-priority about the activities and a high priority related to the operative personnel. In case of the method implementation it was possible to win a top-manager from the company's upper level to support the activities with the required resources (i.e. time and financial aspects). Moreover the high management level was the "mentor" of the integration of the developed PA approach. In this case the management also was committed to support the project activities. However, the top-management of a company cannot be directly involved in every method implementation process, especially when rather simple methods are to be applied to support the individual designer [USHER, 1996]. The mentor serves to protect the implementation team, for example, if departments of the company that are not directly involved in the implementation process try to block the change for any reasons. For a better integration of the mentors in the implementation process it was quite important to report the latest achievement of PARAMASS. Furthermore it was quite important that the results are not only presented by the project manager (they are always interested that their projects are successful) but also by the CAD designers. In this case it was possible to demonstrate to the mentor that the CAD designers are aware of PARAMASS and it shows a more "neutral view" of the achievements. The installed mentor was also invited in the so-called "Demonstration Centre" to get a better understanding of PARAMASS.

7.3.4 Tackling the communication problem

The communication aspect of the method implementation is also one of the most important ones [STETTER, 2000]. It was possible to observe that the communication aspects are multidimensional. This means that the communication of information should be created in different directions and channels. The first important aspect is the communication of the results of the project to the people who are directly involved in the PA method development process. For that purpose, meetings were created in which the latest results and findings related to the different phases of the PA method development were presented. For better communication and visualisation of the latest results a role called the "demonstrator" was created. The main task of the demonstrator was:

- To show the benefits of the developed PA approach;
- To present the latest result of the developed PA approach to the involved participants;
- To present the latest results of the PA approach to the management (foreign minister role);
- To present real examples based on the developed PA approach;
- To promote the developed PA approach;

The first point is the most important one, because the application of PARAMASS should also show some positive results and also improvements related to the created PA parts and assemblies. Albin [ALBIN, 1994] stated that he was able to observe that in most of the cases the method implementation approaches fail because the motivation for change, i.e. the improvement potential, is not communicated to all stakeholders. Furthermore he stated that there were problems in implementing for example Concurrent Engineering (CE) because the improvement potential was not communicated to the top engineering managers.

Another measurement for the communication of the latest results of the developed PA approach was to create a “Newsletter” which reports the achievements and the examples of the created PA CAD parts and assemblies. This was a very effective measurement because different departments had the opportunity to give the latest results of their created CAD parts and assemblies. Furthermore by means of the “Newsletter” it was possible to communicate the problems which had been identified during the development process. Therefore the “Newsletter” should not only be used to demonstrate the benefits but it should also be used as a “communication platform” about the important issues of the PA method development process. In this case an “open” communication of positive and negative issues is quite important. In addition to the Newsletter for a better communication of the results a “PA approach colloquium” was installed. By means of the developed colloquium the different CAD design departments had the possibility to present their latest CAD parts and assemblies with PARAMASS. The important targets of the installed “PA approach colloquium” were:

- To exchange information about the latest achievements of the CAD designers and their activities with PARAMASS.
- To present CAD components which have been designed with PARAMASS.
- To offer a platform for the CAD designers to demonstrates their achievements by means of PARAMASS.
- To offer a platform for other CAD designers to “learn” from other CAD designers from other departments.

7.3.5 Lesson learned during the PA approach planning and development

During the planning and implementing phase the author was able to observe different aspects which helped to plan and implement the developed PARAMASS in a better way. The important aspects are:

- The designers need to be involved at an early stage of the PA method implementation. The creation and development of an initial team and regularly meetings to discuss the further steps are very important. The team members should be from different design departments and the role of them is to be the “PA method ambassador”.

- The targets of the planned project and activities have to be clarified at the beginning of the implementation. A very detailed explanation of the project targets and necessities of the PA method implementation should be clarified i.e. by the designers and the management.
- The designers should have voice in the planning of the PA method implementation activities. This point will help to give the designers the feeling to be perceived and will also help to reduce the resistance of the designers during the PA method implementation.
- The planned activities about the PA method implementation have to be communicated openly and regularly. The designers should have the opportunity to communicate their problems and concerns about planned activities. Creation of an open communication environment is very important. Furthermore by means of an open communication there will be a stronger involvement of the PA designers. They will not have the feeling that the method will be implemented by force from the top management level.
- The management should support the PA method implementation through the whole project. The management should allocate the boundary conditions which are necessary to implement the PA method. A mentorship by the members of the management leads to the importance of the PA method implementation. Furthermore the designers will be supported by the fact that what they're doing is important.
- The management should procure the designers time to plan the learning, training and applying the PA method. The management has to support the designers by allowing them to allocate time which should only be used for training, learning and applying of the PA method.
- The basis of the PA method training is a course of PA CAD. For that reason the designers should have the possibility to visit training for the PA CAD system before starting to work with PA design methods.

7.3.6 Integration of the PARAMASS approach in the PA CAD training

One of the success factors was also that the PARAMASS approach has been integrated into the CAD training programmes. In the past such programmes contained only the functional aspects of the PA CAD systems. That means that the designers get only training of how to use the "functions" which are available by the PA CAD systems. The disadvantages of such a procedure were that the designers get only demonstrated how the different "buttons" and "functions" works. But PA design is more than the single application of the different functions. What the designers need is more an understanding of the philosophy of parametric and associative design systems and how they are able to "manage" the complexity of such systems. Furthermore modern PA CAD systems offer a lot of different functions which can be used by the designers. In case of not using these functions in a methodological way there is a big danger that the CAD system will punish the designers because the created parts and assemblies cannot be modified at later steps of the design process. In some cases there is a need for rebuilding and new construction of such PA components.

The CAD trainers used the PARAMASS approach in their PA CAD training to explain to designers the definition of parameter and parametric design (by means of the PSM approach). They were also able, by means of the ASM approach, to explain to designers the different kinds of associative relationships which can be created. It was also possible to observe that the designers were able to see how important it is to work in a methodological way with such complex PA CAD systems.

The trainers decided to divide the PA CAD system training into two parts. The first is a "theoretical" part which has the target to give designers an understanding about the parameters and associative design from a methodological aspect. The second part was the training of the functions of the PA CAD system. It was possible to connect these two parts by means of different PA CAD components with different levels of complexity.

7.4 Conclusion

This chapter has presented issues in the implementation of the PARAMASS. Based on a questionnaire and the results of a literature survey has identified challenges and problems which have been considered during the implementation phase of methods. Furthermore tackling strategies were developed to consider the identified problems during the implementation of PARAMASS. The team structure which was created for the implementation phase is based on involving and supporting the designers during the introduction of PARAMASS through a pilot project. Furthermore every single team member was installed to tackle one of the problems which have been identified. During the accomplishment of the pilot project it was important that there are experts who have an understanding about PA CAD systems and methods. By means of these experts it can be ensured that possible problems and challenges of the developed PA approach can be tackled in a very fast way. Furthermore there are people available who can give good inputs about the improvement potential of developing and integrating PARAMASS. Beside the above explained factors it can also be concluded that a strong involvement of the CAD designers during the planning and application of PARAMASS is one of the key issues which should be considered. The involvement of the CAD designers in the improvements and development of PARAMASS leads to a very effective working and planning of the activities related to the approach. It can be ensured that by means of CAD designers support there is a certain “commitment” of the designers about the planned activities available. The next chapter will present the qualitative and quantitative evaluation of PARAMASS.

8 Descriptive Study II: The analysing of the implementation and application of PARAMASS

After a short introduction the following chapter will present on analysis of the implementation of the developed PA approach (PARAMASS). Based on the results of the Descriptive Study I and the identified factors, the following section will present a framework which has been developed to assess the changes and improvements through the application of PARAMASS in an industrial context. The following section will then present the results of the Descriptive Study II from the Blessing and Chakrabarti Design Research Methodology. By means of the developed framework it is possible to evaluate the important indicators of the developed PA approach. The evaluation methods have been selected and adopted from different domains. It is very important to say that the purpose of the evaluation framework is to demonstrate the changes though the PARAMASS approach. It is not developed to demonstrate the efficiency of PA CAD systems through the whole product development process. This chapter will also present aspects which are important during the planning and accomplishment of such evaluation processes. But first the next section will present the characteristics of Descriptive Study II.

8.1 General approach of method evaluation

This section of the work presents different approaches which have been developed for the evaluation of different kinds of software, tools and methods. Wigand tried [WIGAND, 1997] to evaluate the indicators of implementing a “cost and performance measurement method”. For example the *“cost and performance measurements criteria in ’monetary’ and ’non-monetary’ level need to be created that focus on the inadequacies which have already been identified during the initial stages of the method implementation process since the methods to be implemented are aimed to tackle these inadequacies”.* Aside from technology related cost and performance measures, a number of other effects like the organisation, qualification, human, and external effects need to be considered. According to Usher the need for a company to be effective in selecting and applying measurements and criteria is critical [USHER, 1996]. Measurements and criteria should be simple to determine, easily obtained, precisely defined, robust, and should appropriately evaluate the objectives and facilitate an understanding and prediction of the process [USHER, 1996].

But these aspects are also very challenging. According to Stetter [STETTER, 2000] classical investment calculations cannot meet the aforementioned demands, because the different factors of method evaluation are not fully considered. Mittelmann [MITTELMANN, 1998] stated that for processes with a low level of structure and/or maturity, 'soft' criteria, which can be adapted to the situation, are much more appropriate than 'hard' measurements which can easily mislead.

Another approach which was presented by Reichwald [REICHWALD, 1996] is the evaluation of information and communication methods and technologies based on the so called 'networked efficiency thinking'. The basis for evaluation in the final analysis of this approach is the extent of effectiveness. The concept of efficiency and effectiveness broadly corresponds to the concept of product development productivity proposed by Duffy [DUFFY, 1998]. In software development, an approach called Goal/Question/Metric (GQM) is widely used for evaluating processes. This approach was developed by [BASILI/ROMBACH, 1988] and successfully applied in industry by, amongst others, [VAN LATUM, 1997] and [FUGGETTA, 1998]. Fuggetta [FUGGETTA, 1998] states that the application of the GQM approach offered improved data collection practices, better interpretation of the data and an enhanced motivation for data collection. The GQM approach represents a systematic approach for tailoring and integrating the objectives of an organisation into measurement goals and their refinement into measurable values. The core element of this approach is the GQM plan. This plan contains three parts:

1. Goal: a goal describes the measurement purpose. A GQM goal is described according to a template with five dimensions expressing the object of measurement, the purpose of measurement, the measured property of the object, the subject of measurement (viewpoint) and the context and environment of the measurement.

2. Questions: a set of questions that refine the goal and characterize the object.

3. Metrics: a set of measurements associated with each question in order to answer it.

Another important element of the GQM approach is a measurement plan. It describes the metrics for each goal and procedures for embedded data collection. For qualitative evaluation of the developed approach the GQM approach can be directly transferred from software to the PA method development process. Furthermore the GQM approach has potential for automating data collection in the method evaluation process. One of the biggest assets of the GQM approach is that it contains different levels which are interconnected with each other and therefore there is a clear target for every created question.

The above presented GQM approach can be used to describe the circumstances and boundaries in which the questions are created. Furthermore it is possible to describe what is the purpose of the question, what is going to be asked and who is involved in the questionnaire. Furthermore it is possible to have a direct link to the question and its target which is one of the important aspects during the creation of questions. It can also be ensured that the questions and the related metrics are defined. For the above mentioned reasons and the different levels of the GQM approach it is possible to have a systematic way to create and document the origin and the purpose of the questionnaire. The next section of the work will define general phases of the method evaluation process which are necessary for the accomplishment of the evaluation process

8.2 General problems of the evaluation process

According to Stetter [STETTER, 2000] the measure "that should be used for evaluating the impact of method implementation is the product development productivity". But in an industrial context enabling such measurements is not an easy task. The reason is that a number of problems have to be considered during the measurement process of the product development processes. Stetter [STETTER, 2000] also stated that these problems are: the measurement indicator problem, the probability problem, the attribution problem, the situation problem and the quantification problem. Further research works also stated that they have made the same experiences with the above mentioned aspects [WIGAND et al, 1997], [REICHWALD/CONRAD, 1995]. The identified problems will now be explained and discussed in detail.

8.2.1 Problem with identification of measurement indicators

Product development processes typically last from months up to more than a few years like in the aerospace industry. As a result, indicators need to be developed that are correlated with a good process result [GIAPOULIS, 1999]. In this context, indicators comprise information that allows the evaluation of the current situation in a product development process. Indicators can be quantitative measurements, for example, the number of product changes in a certain period of time or the number of deviations from the schedule, or qualitative criteria, for example, the stability of the product development process [STETTER, 2000]. However, the correlation of the indicators to the success of product development is, in general, not proven [REICHWALD et al., 1996].

In the present work the identification of the important indicators and factors was one of the biggest challenges. The reason was that for the identification of the indicators a very detailed analysis and understanding of the CAD methods and design processes is necessary. In an industrial context these indicators can only be identified by means of a close working process **with** the designers and the CAD design process participants. Then only by considering this aspect the researcher will be able to have an understanding about the important issues and indicators. By means of a very close cooperation with the CAD designers and CAD process participants it was possible to get very important information about the indicators.

8.2.2 Problems of Attribution

Reichwald [REICHWALD et al., 1996] stated that the direct attribution of useful effects to a single method causes significant difficulties. In a product development system, during the time span of a method implementation, other aspects of the development systems are often changed as well, for example, as a result of scheduled training for the designers involved. Furthermore, as a consequence of the attribution problem, the whole chain of added value has to be considered when evaluating the impact of methods. Related to the present work after the identification of the indicators the most important aspect was to identify changes or improvements related to PARAMASS for tackling the identified indicators. Furthermore the effects which were investigated were related to the identification, determination and presentation of the defined parameters and associative relationships. It should be also investigated if the new developed PA approach enables designers to structure their PA parts and assemblies in a “structured” way. Further aspects of overall evaluation of PA CAD systems in the design process are not planned and considered.

8.2.3 Problem of quantification

The monitoring of quantitative measurements is generally lacking for evaluating the impact of method implementation [GRIFFIN, 1992]. As a result, further criteria that cannot be quantified have to be used in order to evaluate the effectiveness and efficiency of method implementation [GRIFFIN, 1992]. Griffin also reports that during his evaluation process the teams identified a number of benefits attributable to a method implementation that are not quantifiable. Because of different problems, especially the measurement indicator problem, it is usually impossible to avoid the use of qualitative, ‘soft’ criteria, in order to evaluate the impact of method implementation. This aspect was also observed by the author. Therefore a qualitative evaluation of the developed approach was also one of the important aspects of the evaluation process. It was possible to observe that beside the “hard” evaluation facts the “soft” facts also were very important. Furthermore in an industrial context the soft facts were much more important than the hard facts. It can be also possible that despite having good hard quantitative criteria the “poor” usability of a method may cause problems. If designers are not satisfied with the usability aspects of the developed approach it will be quite difficult to retain them for further quantitative evaluations.

8.2.4 Problem of probability

The product development process is characterized by a huge number of influences. For example private problems of single CAD designers, personal preference, unsatisfactory computer systems, the political situation, etc. can all have a large impact on product development processes [STETTER, 2000]. Therefore, the effect of improvements in the development process can sometimes be disguised by probabilistic effects [WILDEMANN, 1993].

8.2.5 Problem of situation determination

According to Reetz [REETZ, 2006] every company is different and has different problems and objectives; it is not possible to build a common coherent system of measurement indicators that reflects every company’s real needs. In addition, generally accepted measurements for evaluating benefits of process improvement are lacking [REICHWALD et al, 1996]. A system of indicators and an actual measurement programme must be defined and constantly refined by each individual company. The determination of the right method and approaches for the evaluation is one of the most important aspects. Therefore the author was very engaged to find methods which are able to define the evaluation process in a very systematic way. That means that the evaluation process defines the important steps and indicators of the CAD parts and assemblies which should be evaluated. In this case it can be ensured that the evaluation process can be simulated in the same situation and way.

8.3 General phases of the PARAMASS

The different steps of the PA approach evaluation process can be divided into preparation, introduction, transfer and debriefing.

8.3.1 Preparation and planning of the evaluation process

During the preparation of the tests and experiments with the CAD designers the experimenter has to ensure that the rooms and areas used for the evaluation process should are ready and the CAD workstations are prepared. It should be ensured if for example the required licenses for the CAD systems are available and the CAD designers can start immediately with the evaluation process. The instruction and the process of the evaluation should be available for all the PA method evaluation participants. This aspect shows a level of professionalism and demonstrated that the experimenter is prepared for the evaluation process. Required files (CAD data, examples, explanations documents etc.) should be prepared for the participants so the tests can starts without any "searching" activities. If there is time it is also very helpful to test the issues which should be created with the PA approach with some colleagues. In this case the experimenter will have the possibility to check if i.e. the selected CAD examples, the questions related to the method evaluation and the time which is set for the evaluation process is sufficient or not.

Related to the CAD design tasks which should be applied and evaluated during the evaluation process it was possible to observe that CAD designers are more familiar with examples which have a direct link to their daily tasks. In case of selecting very easy and simple (i.e. designing a simple cube) PA CAD components it was possible to observe that designers were not very satisfied with the presented examples and made comments like "My components are much more complex" or" I want to see how the PA approach works if I am designing my own CAD components". For that reasons the PA CAD component examples which have been evaluated should be selected and determined with the CAD designers. In this case it is ensured that the designers don't have the feeling that the experimenter tries to evaluate only simple PA CAD examples. For example power-train designers prefer examples of their own CAD components like piston, crankshaft etc. Furthermore for the different categories of designers (with different levels of design, work and CAD system experience) it is quite important to have different categories of CAD components with different complexities. In this case it was ensured that the selected examples consider the different level of PA CAD experiences. Therefore the experimenter distinguished between three different categories of CAD components for the evaluation process:

1. PA CAD components with a low level of complexity: (<50 features): screws, shells etc.
2. PA CAD components with a middle level of complexity: (50-200 features): piston, connection rod, crankshaft etc
3. PA CAD components with a high level of complexity (>200 features): Cylinder heads, cylinder block etc.

By means of these three different categories it was possible to select suitable components for different designers with different levels of skills and experience. The selected categories and characteristics of CAD designers will be explained in the next section. Another important aspect during the evaluation process was that during the test a guideline which describes the evaluation process and the PARAMASS should be prepared and distributed. It is very helpful to work out some hard copies of the guideline for the PA CAD designers. In this way the CAD designers have the possibility to check and review the different evaluation process and the PA approach steps.

Further observations of the researcher showed that the evaluation process and the PA CAD method should be done by an external consultant or the researcher him/herself. By means of this aspect it is ensured that the designers concentrate fully on their tasks. Furthermore in contrast with the designers the researcher has the time to prepare and document the results and information about the evaluation process. During the evaluation process of the developed approach the availability of a 'CAD or method coach' is very important. The reason therefore is that the coaches are able to accompany the designers during the transfer and application of the PA approach in case of problems with the evaluation process or the method itself. The best solution is that the coaches are available during the whole evaluation process so that in case of questions they are able to support the designers.

8.3.2 Introduction of the evaluation process

It is also important that during the evaluation process itself there is a short introduction about each following activity during the test. Furthermore, it is also quite helpful that the designers have a checklist at hand where they are able to see what is going to be evaluated. But it is important not to make the introduction seem so mechanical that the participants have the feeling that the experimenter is reading from the checklists. It should only serve as an orientation for all the participants. Before and during the evaluation process clarifying questions should be allowed. In addition it is also important to explain that the PA approach evaluation process serves to evaluate the PA method but not the PA designers who are involved in the test. Otherwise some of the designers have the feeling that the purpose of the tests to test their ability. If possible the management level should also explain that the purpose of the tests is to evaluate the developed PA approach and not the skills or ability of the CAD designers.

Participation in the PA approach evaluation process was voluntary. In addition the statements and feedback of the designers were kept confidential except where the CAD designers wish to discuss the results openly. By means of the aforementioned aspect it was possible to observe that the readiness of the CAD designers was much higher to tell you more about their opinion and concerns. In general the most important aspects during the introduction can be summarized as follows:

- To create an informal atmosphere during the test phase CAD designers must not have the feeling that the purpose of the evaluation is to test the skills of the CAD designers. It should be clearly communicated that the purpose of the tests are to evaluate the created PA approach.
- Make clear that the results of the tests will be used to find out if the developed PA approach is able to help CAD designers during the modelling process with PA CAD systems.
- Make clear that the participation in the test activities is totally voluntary and the CAD designers are able to quit the tests at any time.
- Make clear that the researcher’s task is to evaluate the developed PA from a neutral view. Furthermore make sure that the interest is to help and improve the design task of the CAD designers.

- It should be possible to ask questions during the test and evaluation phase. Make sure that the tasks which should be accomplished by the designers are totally understood.
- Take time to listen carefully to comments are made by the designers. There are not wrong questions. Don't evaluate questions immediately. Take time to answer the questions. If not sure about the answer, try to return to the question later.
- Give designers time to be able to ask questions. Try to document all the questions made by CAD designers and reflect the questions after the tests.

8.3.3 Identification of different categories of designers

One of the most important issues during the evaluation process is the consideration of different category of CAD designers who are involved in the evaluation activities. Therefore it is quite important that the selected CAD designers are representative for the tests. In most cases it was possible to observe that most of the Heads of Department tend to send their 'best' CAD designers for the test issues. But in general it should be ensured that different levels of CAD designers are involved in the evaluation process. Therefore during the selection of possible participants for test purposes it is recommendable to define a way to categorize the CAD designers. One of the best solutions to be able to select representative CAD designers for the evaluation process is to carry out a questionnaire. The purpose of the questionnaire was to get information about personal detail, attributes skills and knowledge. That means information about age, educational background, qualifications, work experience, method experience and PA CAD systems experience. Therefore a CAD designer Profile-Check-List (PCL) was created to get deeper information about the CAD designers. Furthermore by means of the PCL it was possible to create the so called 'CAD designers skill cube' which contains the three important attributes and dimensions of the participants. These are:

a) Level of knowledge
b) Level of method experience
c) Level of PA CAD system experience.

Figure 55 presents the CAD designer's questionnaire and skills cube. The results of the questionnaire demonstrated that 54% of the designers had a work experience of more than eight years. 31% of the respondents had a work experience between four to eight years and the other designers had a work experience less than three years. Furthermore 85% of the designers had a university degree and 8% were technicians. Related to the PA CAD design experience it was interesting to observe that only 20% of the designers had a PA CAD experience of more than five years. 45% of the respondents had PA CAD experience from two to five years and the other respondents had PA CAD experience less than two years. Furthermore for the author it was quite to important to know what the expectation of designers related to PA CAD systems and methods were. The expectations related to the PA CAD system can be summarized as follows:

1) The PA CAD system should enable designer to modify their PA CAD parts and assembly easier and faster. That means the designers felt that such systems could enable them to create their PA parts and assemblies in a better way.

2) The PA CAD system should enable them to design their PA CAD part with more self confidence and security. That means that the wish of the designers was to be able to handle such complex system in a better way. The designers say that they should say what the PA CAD system has to do but not in the other way. Most of them stated that sometimes the PA CAD systems force them to work in another way than they wish to.

3) The PA CAD system should enable them to modify their created PA CAD components in a simple way.

4) The content of the created PA CAD components should be easy to understand.

The above aspects mentioned by the designers helped to create questions during the evaluation of the PARAMASS approach and to see if the new approach was able to consider these aspects. Furthermore the author also asked questions to explore the expectation of the designers related to a new developed PARAMASS approach:

1) The PARAMASS approach should be applicable and work in real industrial context (see question number 11).
2) The PARAMASS approach should be simple to learn and self-explanatory (see question number 8).
3) The PARAMASS approach should lead to a more straightforward modification of the created PA CAD parts and assemblies (see question number 39).

4) The PARAMASS approach should enable the designers to create simple and well structured PA components (see question number 36).

The above mentioned aspects have also been integrated in the questionnaire during the application and implementation of the method.

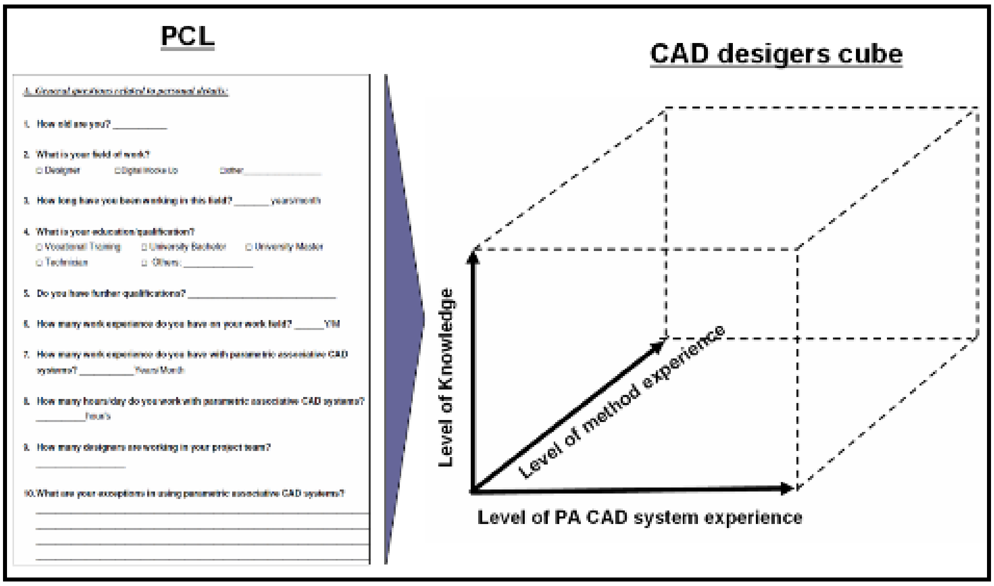


Figure 55: CAD designer's skill cube

By means of the PCL it was possible to clarify and to define four different categories of designer. Table 12 below shows the different classes of CAD designers identified in the test phase

	With design experience (>5 years)	**Without design experience**
With PA CAD system experience (>5 years)	**A**	**B**
Without PA CAD system experience	**C**	**D**

Table 12: Differentiation of the CAD designer classes

The different classes of CAD users can be summarized as follows:

- *Class A:* experienced designers with PA CAD system and long component design experience (Power train design engineers);
- *Class B:* graduates from university with a basic course of PA CAD systems;
- *Class C:* designers with long design experience but no experience with PA CAD systems (worked with other or non parametric CAD systems);

- *Class D:* Not relevant for this work

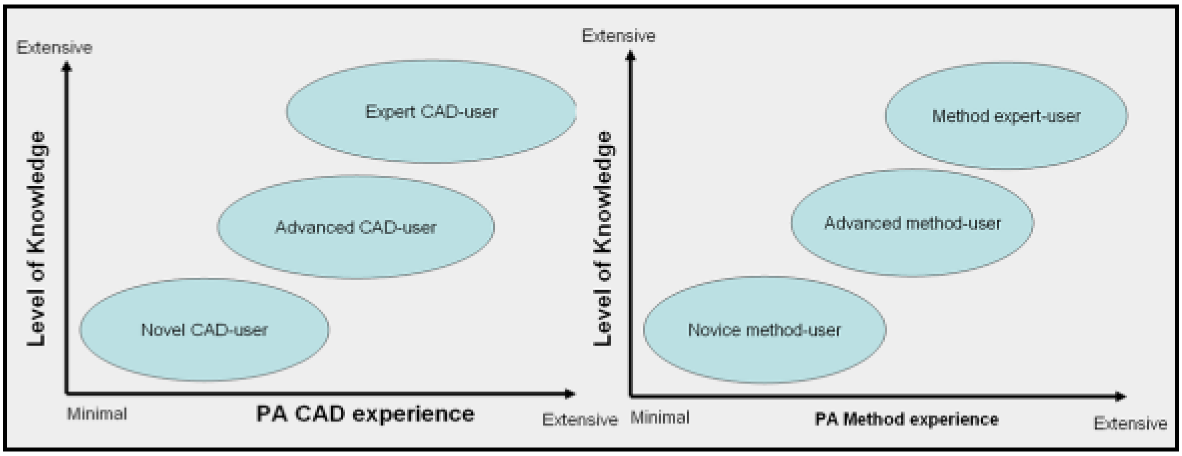


Figure 56: Categorization of different types of PA CAD designers for the test issues

The categorisation of the different kinds of designers helps to see the different performances of different CAD designers with different levels of PA CAD and method experience (Figure 56). The performance results of different CAD designers are presented in Appendix III. Section 8.3.5 describes the procedure of the tests of the evaluation process.

8.3.4 Observed characteristics of different kinds CAD designers.

It was also possible to categorise the characteristics of the different designers who have been observed and evaluated through the study:

a) Observed characteristics of inexperienced parametric associative CAD system user:

From the PA CAD system point of view:

- Users were highly motivated to learn a new parametric and associative system which should help to created better and parameterized CAD models. Furthermore their motivation is based on the expectation that the new PA design system will be able to make their design task and work easier. The researcher was interested to know why they are thinking that the new PA CAD system would make their work easier. Most of the respondents answers that they get this information from the CAD system vendors and their management.
- They hope to ease their design work with the PA CAD system by means of faster modeling and changing process. It was possible to observe that most of the designers think that by means of parametric design they will be able to create different variants of their CAD component.

- They do not have a negative attitude or “prejudices” about the PA CAD system. That means that because of their limited experience with PA systems the designers think positively about the chances and possibilities of the systems and consider only possible advantages which they offer.
- However, inexperienced PA CAD designers underestimate the complexity and the different functions which are offered by the systems. Compared to experienced PA CAD designers who stated that the complexity of the PA CAD systems is one of the big challenges which they have to deal with, inexperienced designer have no imagination about this aspect.
- In particular, they have less imagination about the logical dependencies between the geometrical entities. In PA CAD systems the dependencies between the created features and parameters make it more difficult to delete features and parameters. In case of a wrong “modelling approach” in later steps of the modelling process of the PA CAD components changes of the parameters and associative relationships cannot be done without significant additional efforts. In some cases the CAD components have to be created completely from the beginning.
- The inexperienced designers have less imagination about what the “idea” of PA design means. The understanding what it means to create parametric models and associative relationships is missing.

From the PA CAD methodological working point of view:

- The users have less understanding about why they should work in a methodological manner.
- The users are methodologically “fresh” and “unused”. That means that inexperienced PA CAD designers had not had the possibility to collect experience (positive or negative one) in methodological working with PA systems. Because of this it was possible to observe that during the learning process of the developed PA approach for this kind of users it was easier to learn the method.
- The users also had fewer experiences with possible failure and difficulties during the design process with PA CAD systems. Most of the inexperienced designers did not have an imagination about the difficulties and problems which can be caused through the application of PA CAD systems.

- They also had less experience about the consequences of a lack of clear structuring, identification, determination and presentation of parameters and associative relationships.
- The CAD-inexperienced designers are overwhelmed by the different functionalities which are offered by the PA CAD systems.

b) Observed characteristics of experienced parametric associative CAD system user:
From the PA CAD system point of view:

- They understand that a certain level of logical thinking is necessary. (“Think before you move”). It was possible to observe that CAD experienced designer’s comment that it is quite important to have a clear understanding about what they are going to do next with PA systems. They stated that it is quite important to have clear understanding about the parameters and associative relationships of the created PA CAD components.
- They know about the functional possibilities and “powerfulness” of the systems. Because of the experiences and faults which they have made during the application of systems experienced PA CAD designer are more careful.
- They have learned that there are logical dependencies between the geometrical entities and parameters.
- They have a better feeling about “parametric” and “associative” design. That means that they were able to collect firsthand experience with PA CAD systems.
- Nevertheless, most of the designers and user are surprised over the complexity of the PA CAD system.

From the PA CAD methodological working point of view:

- Despite the additional work which is related to the learning new methods there is a huge readiness to apply methods.
- They had the possibilities to try different ways and methods to design their own parts and assemblies with PA CAD systems. Despite of this fact it was possible to observe that the majority of the designers are interested in new methods and approaches.
- They have understood that without a systematic way the design process with PA CAD systems will be quite difficult.

- They have experiences with possible failure and difficulties during the design process with PA CAD systems.
- They have experiences about consequences in case of failing to have a clear structuring, identification, determination and presentation of parameters and associative relationships.

8.3.5 Definition of the evaluation procedure

Beside the different CAD design categories it was important to create a procedure for the evaluation process. The target of the evaluation process was to accomplish tests and experiments to analyze the performance of the designers (design groups) related to working <u>with</u> and <u>without</u> the developed PA approach (PARAMASS). Furthermore the described procedure should help to measure significant changes during the identification, determination and representation of the parameters and associative relationships of the created CAD. Therefore two different groups of designers were created. The first group was able to work with CAD components which were created with the developed PA approach. In addition the tasks of the first group were to identify, determine and modify predefined parameters (i.e. geometrical and process parameters) and associative relationships of already created CAD components. The second group worked without the PARAMASS approach and they were also required to try to identify the same parameters and associative relationships. It is quite important to say that both of the groups worked with the same CAD component (piston, Oil pan, Cylinder head etc).

The created evaluation procedure can be divided into three different phases. The first phase contains as aforementioned the Profile-Check-List (PCL) for getting background information about the participants of the evolution process. The second phase which was the main part of the procedure contains sub-steps which were necessary to be able to perform different tasks related to the evaluation of the designed CAD components. These tasks involved predefined actions which should be done by the CAD designers. These sub-steps contain tasks like: a) identification of different parameters and associative relationships b) determination of design parameter inputs and outputs of the created CAD components and c) modification of parameters and associative relationships of the created CAD components. The role of the researcher was to measure the time and the number of the tasks which have been accomplished by the CAD designers. This enabled the measurement results of the evaluation process to be collected and documented in a systematic way. The designed measurement protocol which has been used during the evaluation procedure will be explained in the next section.

At the end of the second phase the CAD designers got a second questionnaire related to the usability aspects. The questionnaire which was created for the evaluation process will also be explained in the next section. Finally the designers which were involved in the evaluation process had the possibility to explain their experiences about the evaluation process. Here it is quite important to give the CAD designers the possibility to discuss the issues in a very open way. In this way the author was able to learn about possible improvements and weaknesses related to the evaluation procedure and the applied PA approach itself. Figure 57 presents the procedure of the evaluation process with the three phases identified.

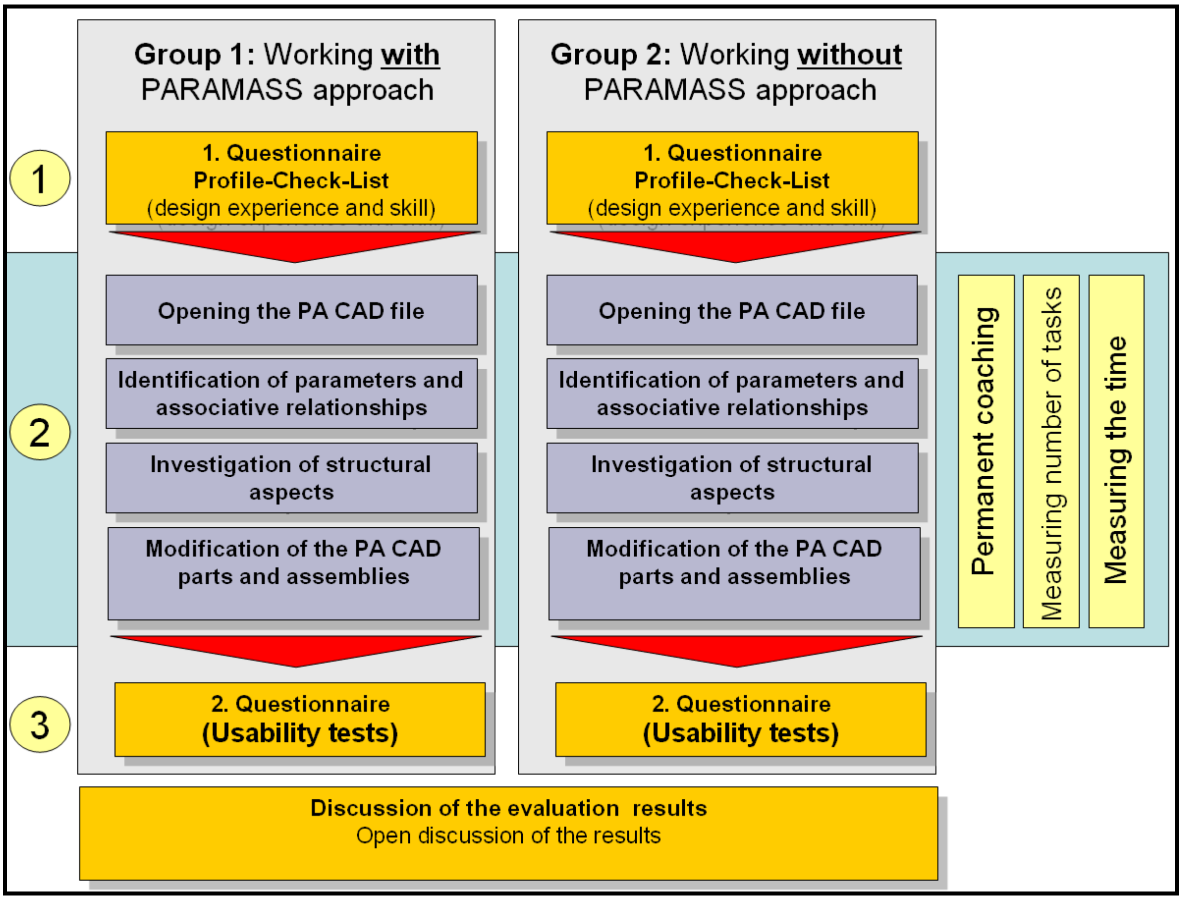


Figure 57: Procedure of the evaluation tests

8.4 Development of the evaluation framework for PARAMASS

The following section of the work describes an evaluation framework for PARAMASS to assess the different aspects of the approach. The target of the evaluation process was to evaluate the key-indicators which have been identified during the descriptive studies and the literature survey. Furthermore it should help to demonstrate the changes and possible improvements which were created through the application of the PARAMASS approach. The framework for the evaluation can be divided into two main sections (see Figure 58). The main target of the questionnaire and interviews was to evaluate its usability aspects i.e. learnability, applicability and satisfaction. The quantitative indicators are characteristics of a product development process or in this case a method that can be measured, for example, by the means of determining the time needed for performing the method step. A number of measurements that could potentially be used for evaluating the impact of the developed approach were collected from literature and from the experience gained in the application of case studies.

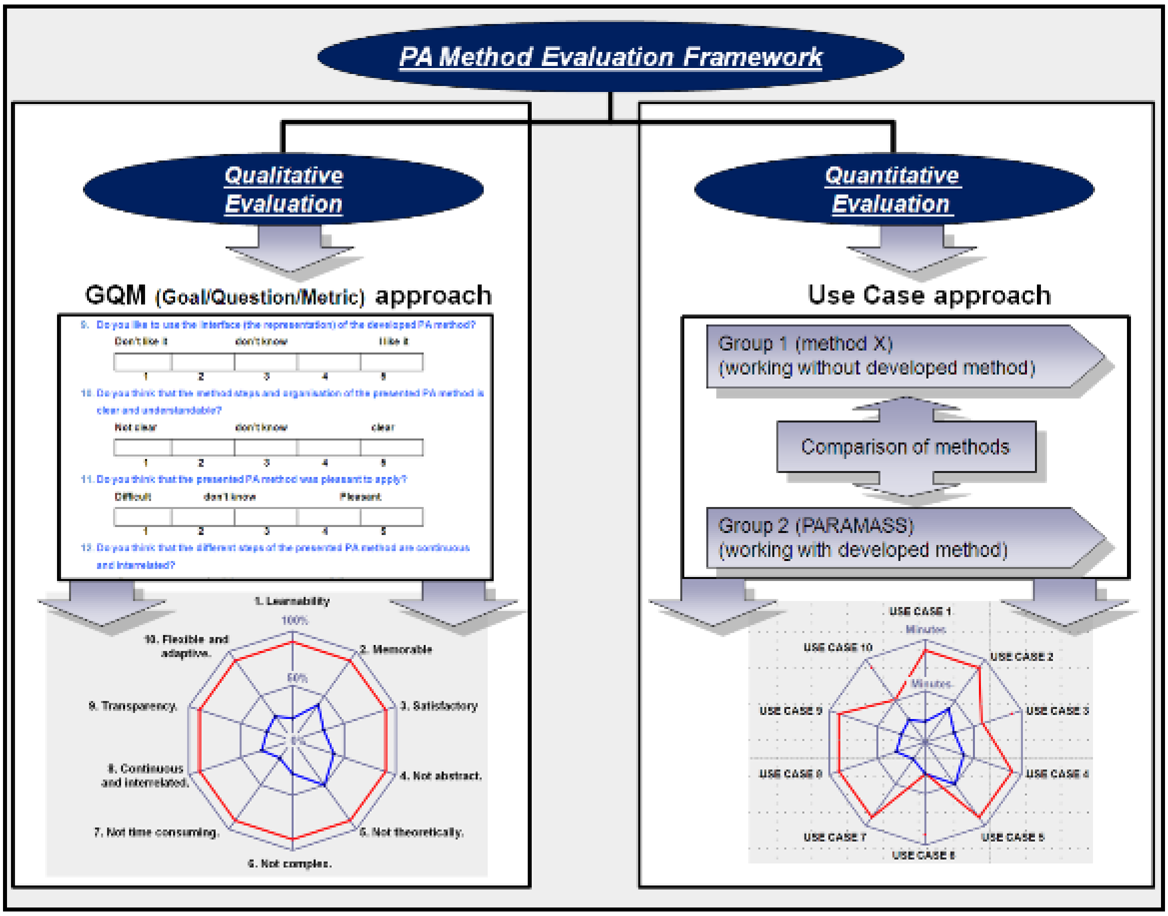


Figure 58: Evaluation Framework of the developed PA approach

8.4.1 Qualitative evaluation of the PA approach from Usability aspects

Before starting to describe the qualitative aspects of the evaluation framework it is important to give a short overview of the qualitative evaluation aspects especially from usability measurement aspects. This section will give an overview of the origin and the definition of the term 'usability'. Furthermore during the application of the developed PA approach the author was able to interview designers and carry out a questionnaire about the usability aspects of PARAMASS. A number of potential criteria for evaluating the impact of a method implementation are summarised in Table 13 [STETTER, 2000]. Table 13 shows some different aspects of qualitative analysis. ISO 9241-11 [ISO 92411, 1998] defines usability as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction".

Criterion	Explanation/Question
Transparency	Was the capability of the concerned people to achieve an overview of all aspects of the development process that are relevant to them increased?
Stability	Was the capability to continue managing the process under changed circumstances increased?
Flexibility	Was the capability to react to changed boundary conditions, by means of quick and flexible adaptations of the process, increased?
Motivation	Was the willingness of the designers to voluntarily participate in the product development process and improvement processes increased?
Documentation	Was the degree of storing relevant information, used or generated in a product development for later used, increased?
Conformity	Was the degree to which the documents and artefacts that are used in daily work match those that were proposed within the method or norms and standards increased?
Human situation	Was the general working situation of the employees reduced, for example, by means of more interesting tasks, less strenuous tasks, more variety of tasks, or reduced repetitive activities?

Table 13: Potential qualitative criteria [Stetter, 2000]

According to Lindgaard [LINDGAARD, 1991], Usability is the ease of learning and using computer systems from the experienced and inexperienced user's point of view. Classifications of Usability evaluation methods differ from author to author. Riihiaho [RIIHIAHO, 2000] defined that "*Usability is a narrow concern compared to the larger issue of system acceptability, which basically is the question of whether the system is good enough to satisfy all the needs and requirements of the users and other potential stakeholder, such as the user's clients and managers".* The overall acceptability of a system or method is a combination of the social acceptability and its practical acceptability. Given that a system is socially acceptable, it's practical acceptability within various categories, including traditional categories can be analyzed such as cost, support, reliability, compatibility with existing systems, etc., as well as the category of usefulness [RIIHIAHO, 2000]. Furthermore usefulness is the issue of whether the system can be used to achieve some desired goals. Figure 59 shows the simple model of system acceptability outlined here.

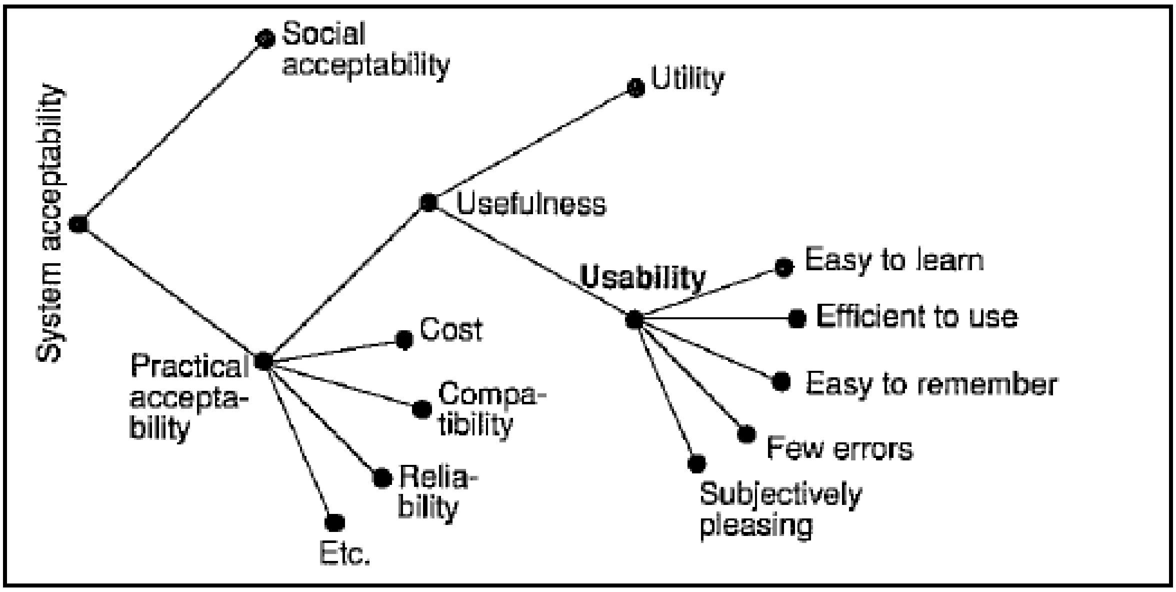


Figure 59: Important aspects of Usability

According to Grudin [GRUDIN, 1992] Usability has multiple components and is traditionally associated with five Usability attributes:

Learnability: The system should be easy to learn so that the user can rapidly start getting work done with the system. Learnability is in some sense the most fundamental Usability attribute, since most systems need to be easy to learn, and since the first experience most people have with systems is that of learning to use it.

Efficiency: The system should be efficient to use, so that once the user has learned the system, a high level of productivity is possible. To measure the efficiency of use for example for experienced users, one obviously needs access to experienced users. For systems that have been in use for some time, "experience" is often defined somewhat informally, and users are considered experienced either if they say so themselves or if they have been users for more than a certain amount of time, such as some months. Experience can also be defined more formally in terms of numbers of hours spent using the system, and that definition is often used in experiments with systems and methods without an established user base: Test users are brought in and asked to use the system for a certain number of hours, after which their efficiency is measured.

Satisfaction: The system should be pleasant to use, so that users are subjectively satisfied when using it; they like it. One of the most important Usability attributes is the subjective satisfaction, which refers to how pleasant it is to use a certain system or method.
Momorability: The system should be easy to remember
Errors: The system should have a low error rate, so that the users make few errors during the use of the system.

The evaluation of PARAMASS can be divided into two different sections. The first sections which contains the qualitative evaluation of the developed approach, is a questionnaire applied after the application of the PARAMASS. It was possible to ask 61 designers about their experience with the approach. As mentioned before the questionnaire was a mixture of closed and open questions, divided into two parts. The basic conditions of descriptive studies are listed in Table 14.

Environment	Automotive Industry and suppliers
Participants	61 power train engineering designers from automotive company and suppliers
Collection methods	Questionnaires and interview
Time constraints	100 minutes for 30 questions
Team size	Groups of 10 people in different CAD design workshops
Number of cases	61 questionnaires
Total duration	6 Months

Table 14: Basic conditions of the questionnaire

The second part contained questions related to the investigation and clarification of the defined Usability issues of PARAMASS. By means of the carried out questionnaire and semi-structured interviews the author was able to get information about the Usability aspects which are linked to the above defined Usability aspects like learnability, effectiveness, satisfaction and memorability. For the identification of these aspects a set of 30 questions has been created. Table 15 demonstrates an example of the created questions based on the GQM approach. The question which has been asked is related to the learnability of the developed approach and the respondents had the possibility to choose between different answers.

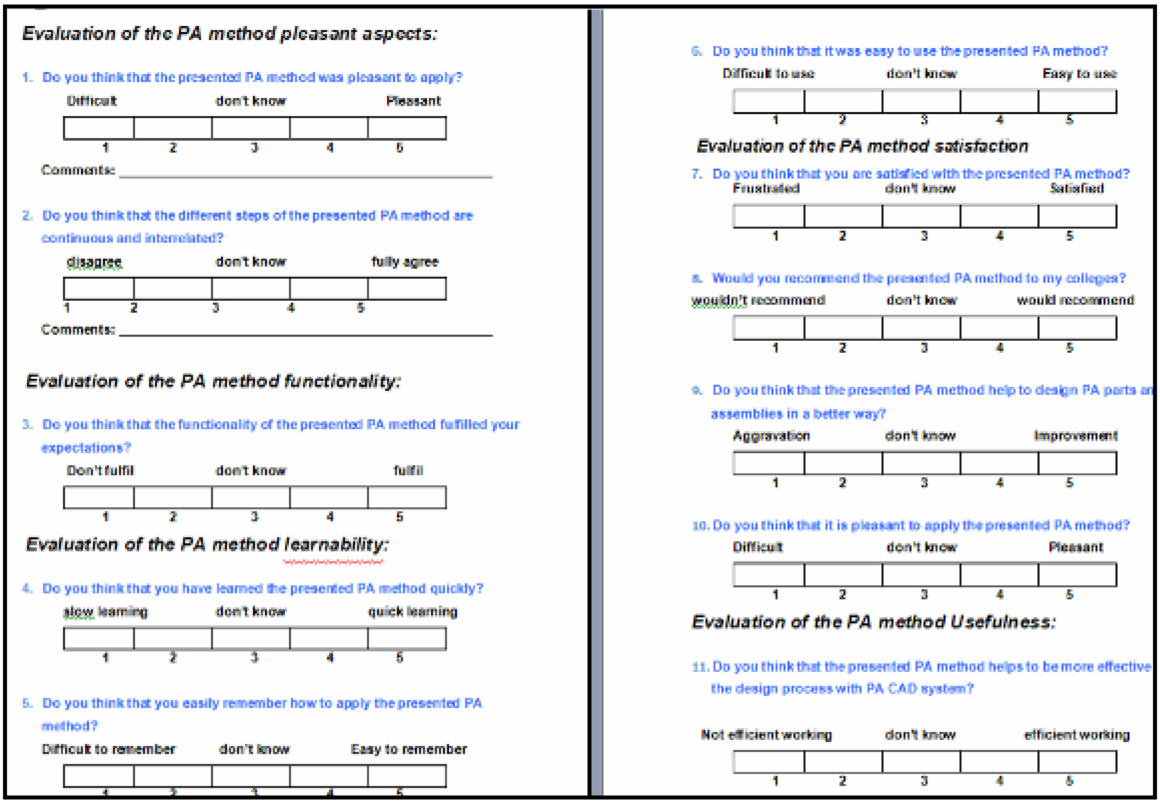
Do you think that you have learned the presented PA method quickly?

slow learning		don't know		quick learning
1	**2**	**3**	**4**	**5**

<u>**Goal:**</u> *<u>Object:</u>* Testing/Experiment phase of the PA design method *<u>Purpose</u>*: Evaluation of the PA method learning/Usability of the PA method *<u>Viewpoint:</u>* Designer *<u>Environment</u>*: Evaluation of the Pilot project in real industrial context.
<u>**Question:**</u> Do you think that you have learned the presented PA method quickly?
<u>**Metric:**</u> Number of positive or negative feedbacks of the designers which are related to the question about presented PA method learnability.

Table 15: GQM application for the questionnaire

Figure 60 presents some of the questions asked for the evaluation of the Usability aspects. The full questionnaire and the results based on the GQM approach are given in Appendix III.



Evaluation of the PA method pleasant aspects:

1. Do you think that the presented PA method was pleasant to apply?

Difficult		don't know		Pleasant
1	2	3	4	5

Comments: ________

2. Do you think that the different steps of the presented PA method are continuous and interrelated?

disagree		don't know		fully agree
1	2	3	4	5

Comments: ________

Evaluation of the PA method functionality:

3. Do you think that the functionality of the presented PA method fulfilled your expectations?

Don't fulfil		don't know		fulfil
1	2	3	4	5

Evaluation of the PA method learnability:

4. Do you think that you have learned the presented PA method quickly?

slow learning		don't know		quick learning
1	2	3	4	5

5. Do you think that you easily remember how to apply the presented PA method?

Difficult to remember		don't know		Easy to remember
1	2	3	4	5

6. Do you think that it was easy to use the presented PA method?

Difficult to use		don't know		Easy to use
1	2	3	4	5

Evaluation of the PA method satisfaction

7. Do you think that you are satisfied with the presented PA method?

Frustrated		don't know		Satisfied
1	2	3	4	5

8. Would you recommend the presented PA method to my collegas?

wouldn't recommend		don't know		would recommend
1	2	3	4	5

9. Do you think that the presented PA method help to design PA parts an assemblies in a better way?

Aggravation		don't know		Improvement
1	2	3	4	5

10. Do you think that it is pleasant to apply the presented PA method?

Difficult		don't know		Pleasant
1	2	3	4	5

Evaluation of the PA method Usefulness:

11. Do you think that the presented PA method helps to be more effective the design process with PA CAD system?

Not efficient working		don't know		efficient working
1	2	3	4	5

Figure 60: Questionnaire of evaluation of the Usability aspects of PARAMASS

The results of the Usability aspects demonstrated that the designers realized subjective improvements through the application of PARAMASS. Especially questions related the Usability aspects like learnability, ease of application and satisfaction of PARAMASSS have been asked. 76% of the respondents agreed that PARAMASS is easy to learn (see Figure 61).

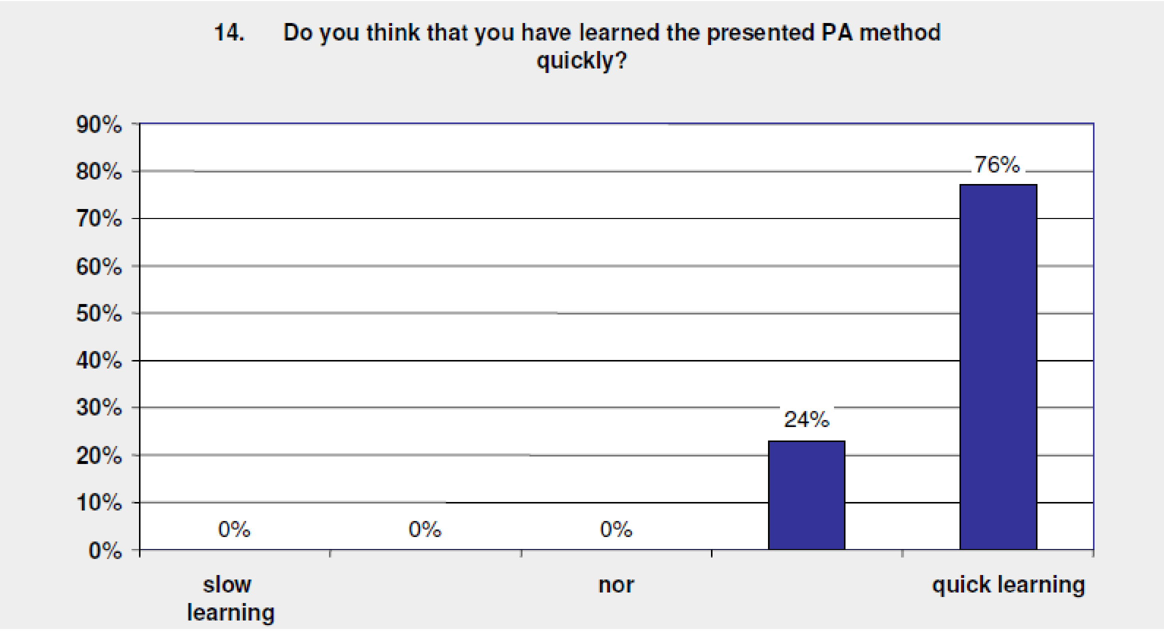


Figure 61: Question related to the learnability of the developed approach

The reason was that the designers mentioned that the developed approach has only three main phases which are easy to understand. Another aspect was that the presentation of the PA approach is based on the V-model therefore the designers are familiar with the logical steps of this approach. However 24% of the respondents mentioned that they need a certain time to be familiar with the approach and therefore were not able to make very positive statements about its learnability. Related to the application aspects it was possible to observe that in general PARAMASS is easy to apply. 69% of the respondents agreed that, by means of the new approach it is easier to identify and determine the relevant parameters (see Figure 62).

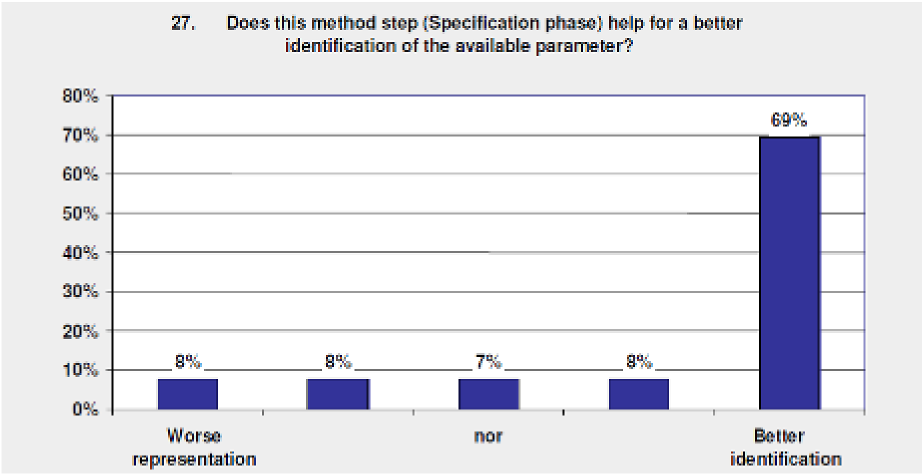


Figure 62: Question related to the specification phase for identification of parameters

In addition it was also possible to observe that most of the designers have a high satisfaction during the application of the PA approach. The reason was that the designers were able to realize their benefits during the identification, presentation and determination of the relevant parameters and associative relationships. Only the designers inexperienced with PA CAD had difficulties to accept that working with PA CAD systems require a certain methodology. They stated that they are surprised that "A new PA CAD system which should ease their work needs a certain approach to work". Related to the aspects which are defined for the evaluation of PARAMASS steps it was possible to observe that the subjective perception of the defined PARAMASS is quite positive. 92% of the respondents agreed that by means of the developed PARAMASS the relevant parameters (product, physical and process parameters) can be represented in a better way (Figure 63).

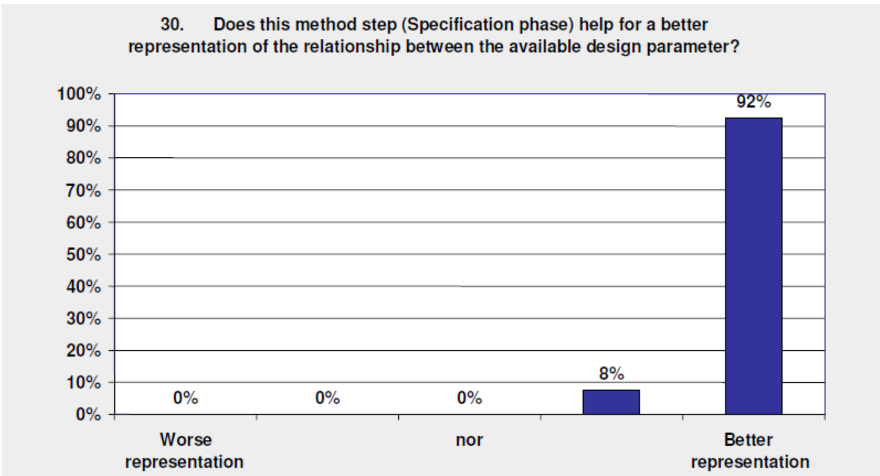


Figure 63: Question related to the specification phase for representation of parameters

Furthermore 73% of the designers mentioned that by means of PARAMASS it is easier to identify the relevant associative relationships. The reason is that the associative relationships can be identified from the part structure of the CAD models. By means of the method the product and process associative relationships can be stored in the defined places and therefore in case of reusability the designers mentioned that they are able to catch the information faster than without a method. From the structuring aspect of the developed PA approach it was possible to observe that 92% of the respondents think that the PA approach has advantages to structure the relevant parameters and associative relationships. Designer mentioned that by means of standard structure templates of their CAD assemblies and components it is easier to order the relevant parameters and associative relationships in the different container information. For example if designers have parameter information which is related to the down-stream processes by means of the standard templates of the CAD models it is possible to store this information inside the template. In case of reusing the created CAD components the information can be attached from the CAD structure. Table 16 demonstrates the difference between the design process with the developed PA approach and without the approach. It is very obvious that before the introduction of the developed approach (results of the Descriptive Study I) the respondents had more difficulties to identify and determine the relevant parameters and associative relationships.

	Working without PA approach (Yes)	**Working with PARAMASS (Yes)**
I am able to identify the PA design parameters?	24%	69%
I am able to determine the PA design parameters?	23%	72%
I am able to identify the associative relationships?	21%	73%
I am able to determine the associative relationships?	26%	71%

Table 16: Comparison of the Descriptive Studies I and II

Figure 64 shows the complete result of the Descriptive Study II for evaluation of the developed PA approach. The complete results can be taken from Appendix III. The red line represents the results without the method and the blue line represents the results after the application of the PARAMASS approach.

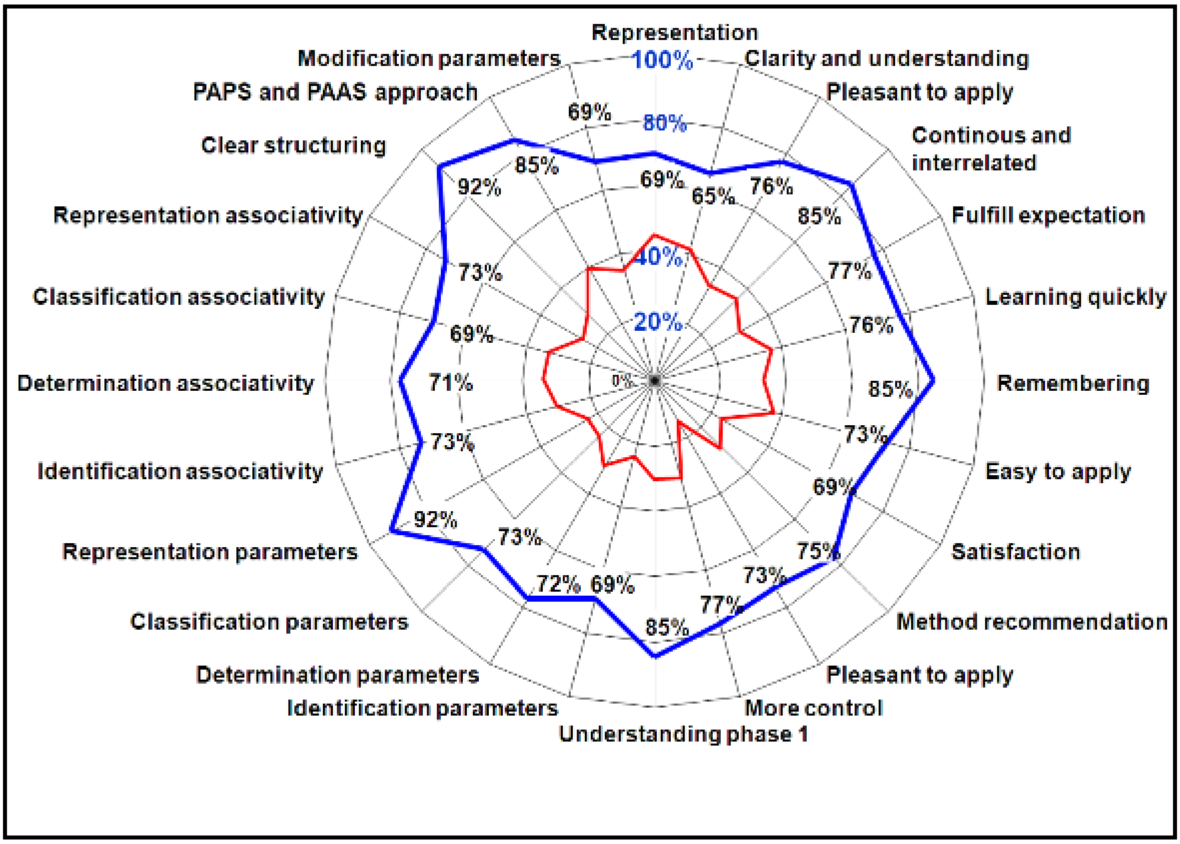


Figure 64: Results of the qualitative evaluation of the developed PA approach

8.4.1.1 Conclusion and limitations of the qualitative evaluation

By means of the qualitative analysis it was possible to evaluate the qualitative criteria of the developed PARAMASS. Furthermore it was possible to make weaknesses and improvements of PARAMASS visible. But the main task of the qualitative evaluation process was not only to define an approach for the demonstration of the positive aspects of the PARAMASS. It should also be considered that the qualitative evaluation process is very time consuming and needs careful planning. The evaluation process took 6 months to plan and carry out.

8.4.2 Quantitative evaluation of the developed PA approach

This section presents the quantitative evaluation of PARAMASS. In particular, it will present the procedure which has been selected to evaluate the PA approach based on different case studies. As previously noted, quantitative measurements are characteristics of a product development process that can be measured, for example, by determining the time needed for performing a certain process step. A number of measurements that could potentially be used for evaluating the impact of a method implementation were collected from literature and from the experience gained in the case study [USHER, 1996], [STETTER, 2000]. However, it is solely aimed at clarifying what kind of measurements can be used for comparing different states of product development processes. Table 17 presents measurement criteria for the quantitative evaluations.

Measurement	Explanation/Question
Satisfaction of internal customers	Was the quality of the output of a process section, used by any internal customer, enhanced?
Estimated product cost	Does an estimate of the production cost of a product, based on preliminary data, for example, concept sketches, indicate a reduction?
Fulfilment of requirements	Does a prediction of the fulfilment of customer requirements, based on preliminary data, for example, concept sketches, indicate an increase in fulfilment?
Flaws	Was the number of flaws in a product or a production process at a certain point in time reduced?
Changes	Was the number of necessary engineering changes after product release decreased?
Iterations	Was the number of engineering changes that are required before product release reduced?
Reoccurring flaws	Was the number of flaws of the product that were not tackled in the first approach reduced?
Planning accuracy	Were discrepancies between initial and intermediate planning and actual effort and time reduced?
Wasted effort	Was wasted effort and/or delay generated because of process flaws decreased?
Process time	Was the amount of time a process section requires for achieving the intended result reduced?
Idle time	Was the amount of time any artefact (including information) is present 'within' one process section and cannot be used by any other process section minus the actual process time reduced?
Set-up time	Was the amount of time spent for preparing (physically or mentally) a certain activity reduced?
Co-ordination	Was the effort necessary for co-ordinating different activities reduced?

Table 17: Different possibilities for qualitative analysis [STETTER, 2000]

The measurements listed in Table 17 cannot be used in an industrial context without verification of their applicability to certain cases. The implementation of these measurements in real-industrial processes was a really challenging task that demands an in-depth knowledge of all of the aspects of these processes. The results should be reviewed for their validity and significance. Related to the quantitative evaluation in this study it was quite important to identify factors which could be measured during the evaluation process. Therefore one of the necessary prerequisites for measuring the PA approach characteristics was the decomposition of the PA approach steps into smaller units. That means that it was quite difficult to quantify the "whole" approach. Therefore the quantitative evaluation considered PARAMASS by defining different tasks for measurement of the performance. By decomposing the PA approach in smaller measurement units it was possible to evaluate the approach more accurately. The decomposition of the procedure during the evaluation process was based on the PA approach steps themselves. During the quantitative measurement a triangulation, i.e. use of a variety of sources, was performed in order to validate the collected data. In the evaluation, different tasks related to identification, determination and representation of the relevant parameters (geometrical, process and product parameters) and associative relationships was developed and formulated. The measurements were made by recording the time during the accomplishment of the tasks with and without the PA approach. One of the best procedure solutions of the quantitative evaluation process is the Use Case based approach, which defines exactly the environment of the evaluation process. The selected quantitative approach was based on Use Cases adopted from software and business process evaluation. It was important to define a procedure which allowed a very exact planning of the evaluation process. The important aspects of the quantitative criteria are shown in Figure 65.

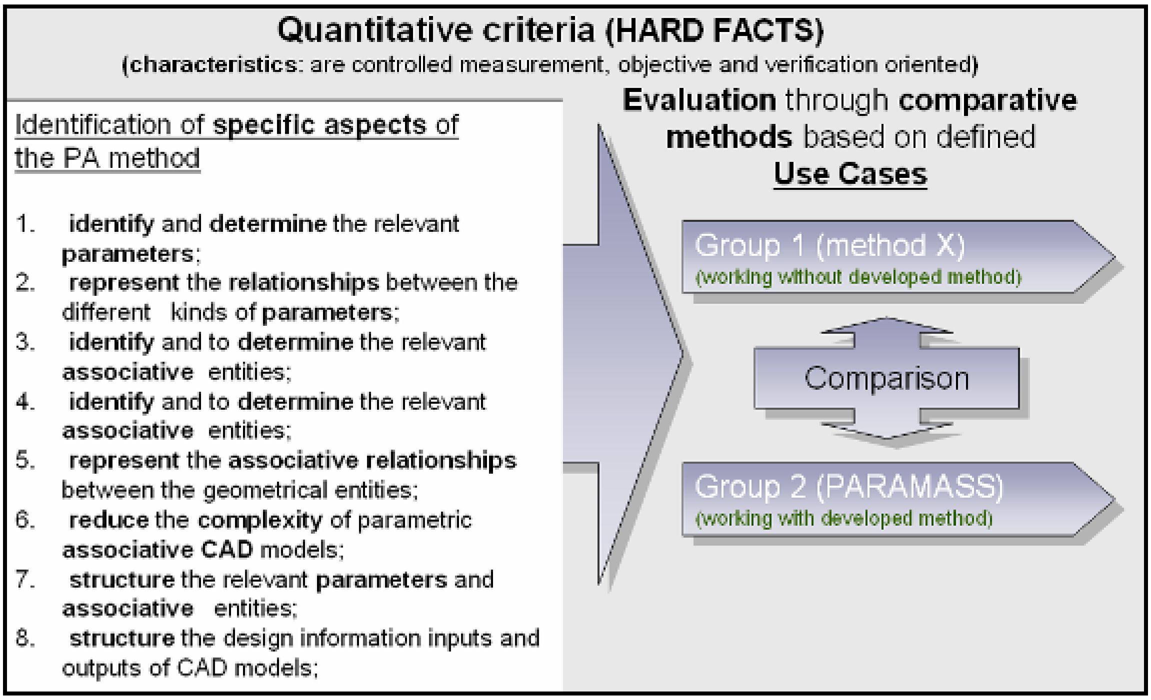
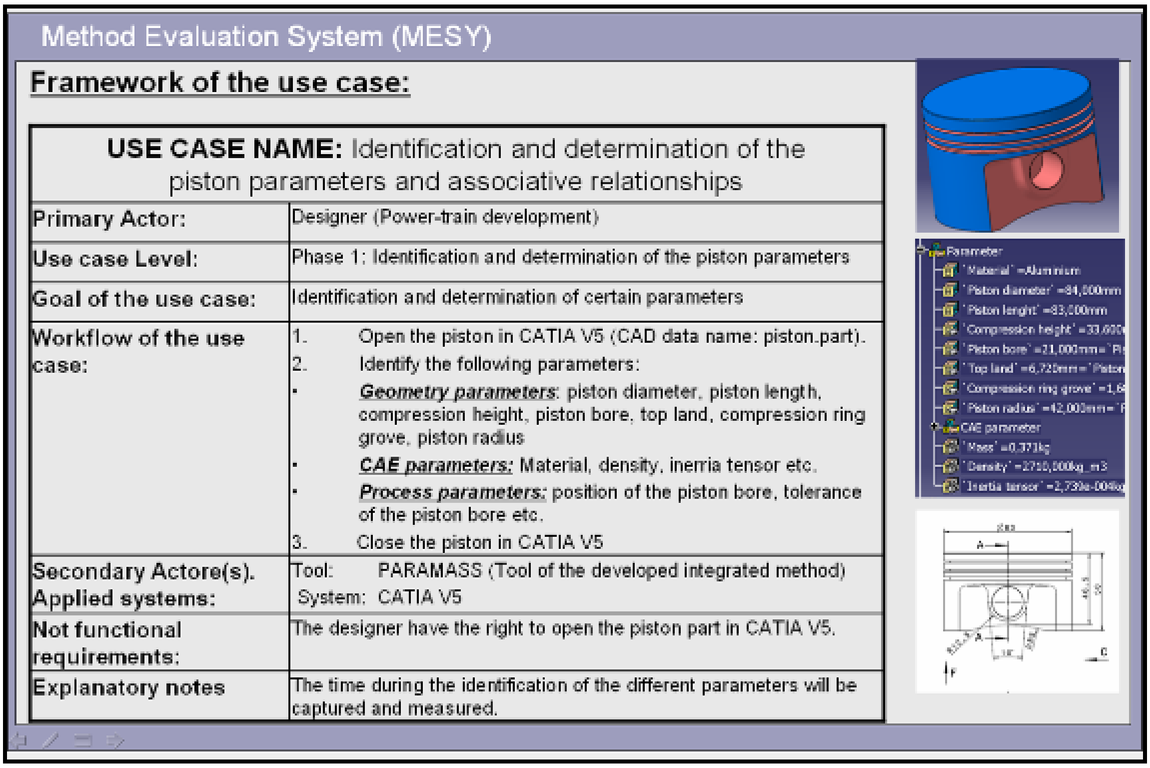


Figure 65: Quantitative evaluation criteria for the developed PA approach

8.4.2.1 Definition of Use Cases

The most important question was “how will it be possible to evaluate and quantify the changes through the developed method?” According to Jacobson “A Use Case is a narrative document that describes the sequence of events of an actor (an external agent) using a system to complete a process [JACOBSON, 1992].” It is composed of a collection of scenarios describing: (i) alternative ways of achieving a goal, (ii) unwanted endings and (iii) the reaction to potential exceptions that could arise at different times during otherwise normal scenarios [JACOBSON, 1992]. Each Use Case captures: a) the actor (who is using the system?) b) the interaction (what does the user want to do?) and c) the goal (what is the user's goal?). Related to the evaluation of the developed PA approach, Figure 66 shows an example of such Use Cases. In this example, a designer from the power train department is involved in the evaluation process. The goal is to investigate the first phase (specification phase) of PARAMASS to explore if it helps for a better identification of certain parameters and associative relationships. The table describes the workflow steps which are necessary to accomplish the Use Case. In addition there is also information about further actors (can be also a system or method) who are involved in the evaluation process.



USE CASE NAME: Identification and determination of the piston parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Identification and determination of the piston parameters
Goal of the use case:	Identification and determination of certain parameters
Workflow of the use case:	1. Open the piston in CATIA V5 (CAD data name: piston.part). 2. Identify the following parameters: • ***Geometry parameters***: piston diameter, piston length, compression height, piston bore, top land, compression ring grove, piston radius • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:*** position of the piston bore, tolerance of the piston bore etc. 3. Close the piston in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the piston part in CATIA V5.
Explanatory notes	The time during the identification of the different parameters will be captured and measured.

Figure 66: Framework of the developed Use Cases

The general benefits of the applied Use Cases are:

- They encourage designers to consider the characteristics of tasks and their environment.
- Usability issues can be explored at a very early stage in the design process of the method.
- Scenarios can help to identify and compare quantitative targets and likely task completion times.
- Scenarios can also be used to generate contexts for evaluation studies.

- Only minimal resources are required to generate scenarios.
- The technique can be used by developers with little or no human factors expertise.

Furthermore, by means of the structure of Use Cases it is possible to describe what, by whom and in which way the designers have to act. In this way it can be ensured that during the tests all of the participants exactly know what they have to do and how they should act [JACOBSON, 1992]. Related to the evaluation of PARAMASS it was very important to create the Use Cases in a way which allows the evaluation of the different phases of the approach. Furthermore the definition of the possible scenarios was implemented in the regular team meetings of the test participants. In this way all the process participants had the same understanding about the content of the Use Cases and the progress. At the end of the quantitative evaluation 120 Use Cases were defined for the 3 phases of PARAMASS. Figure 67 shows also the structure of the Use Cases defined for the evaluation of the different method steps. The numbers one two and three demonstrates the Use Cases created for each PA method phase.

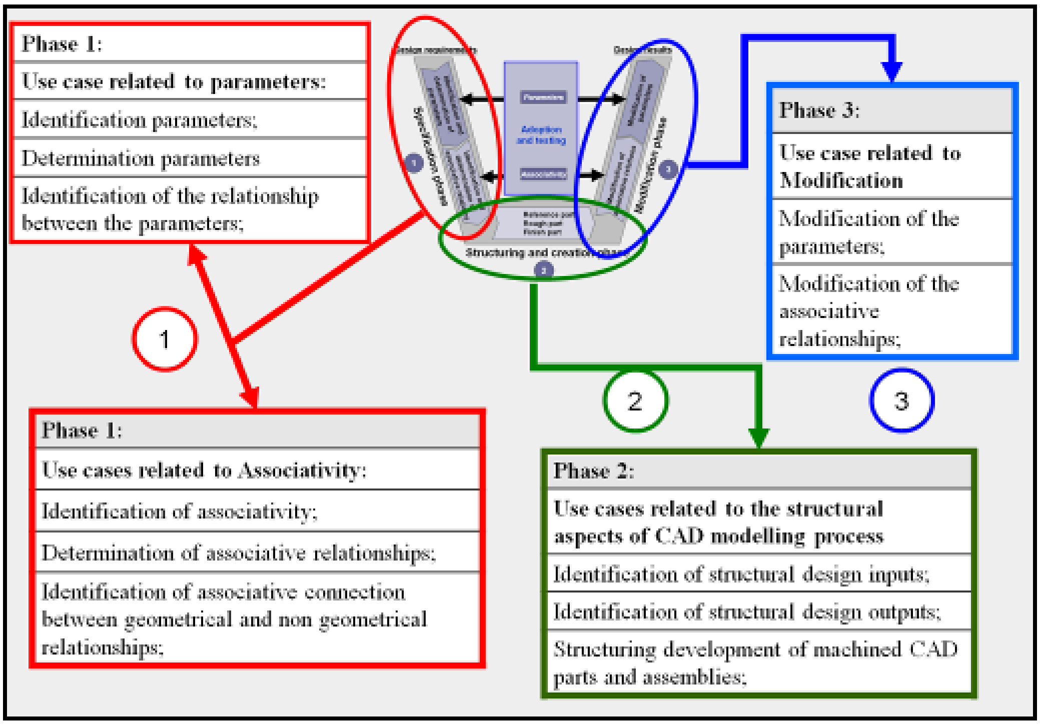


Figure 67: defined Use Cases of the different PA approach phases

During the definition of the relevant Use Cases it was important to select the right scenarios and examples. Therefore the identification of possible scenarios was discussed and developed in cooperation with the CAD designers. In this way it was ensured that realistic scenarios were generated. Otherwise the parameters and associative relationships which have been selected for the evaluation can be “wrong” and the evaluation made on false considerations. Therefore the recommendation is:

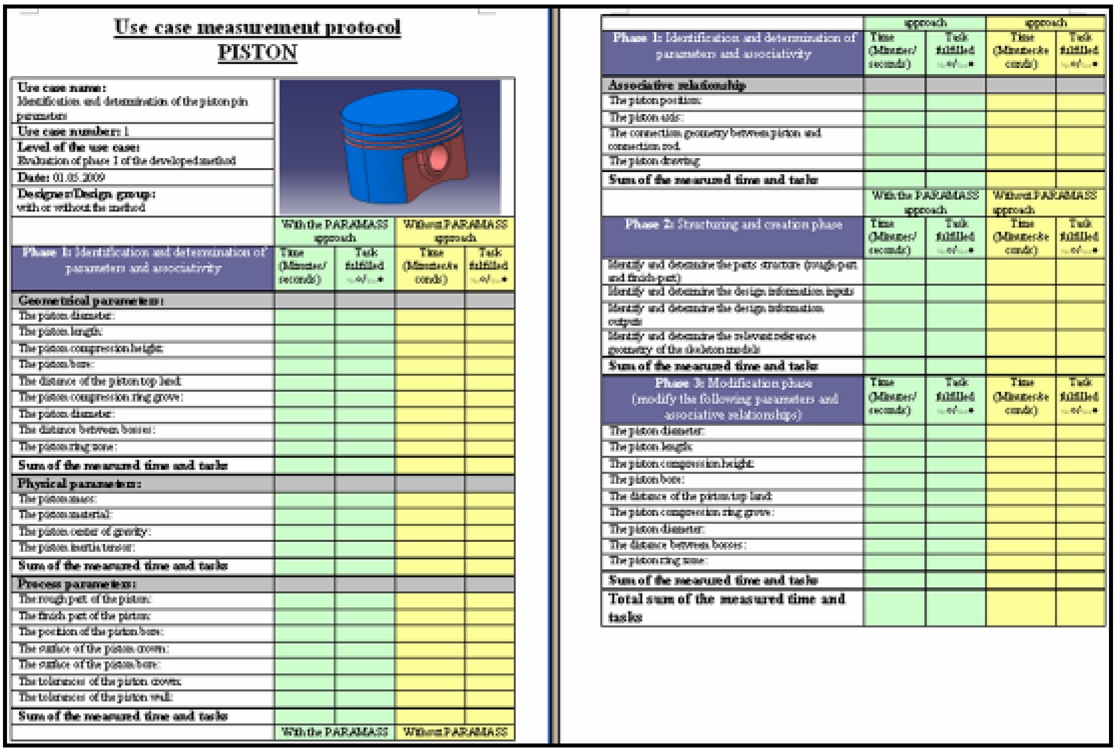
- The determination of the PA CAD parts for test purposes should be done with the CAD designers. In this case it can be ensured that the right CAD examples are selected.
- The selection of possible parameters and associative relationships should be done with the CAD designers. Only the designers have a full understanding of the different kinds of parameters and associative relationships which are relevant for the design process.
- The created Use Cases should be discussed with the CAD designers. In this case it can be ensured that the created Use Cases and scenarios are more realistic and industrial based.

8.4.2.2 Documentation of the quantitative results

This section will describe the measurement protocol which was necessary to document the quantitative evaluation process. One of the most important questions during the quantitative evaluation process was “how is it possible to document the performance of the different groups of designers during the accomplishment of the tests with and without the PA approach?” For that reason a protocol was defined to collect the measured times during the application of the Use Cases. In this way it was possible to list the time measured during the design process with and without the PARAMASS approach. Two aspects were documented in the defined protocol. The first aspect was the measured time and the second aspect was the fulfilment of the tasks. The qualitative measurement protocol was divided into different sections.

The top of the measurement protocol contains general information about the CAD component which should be evaluated. In the example in Figure 68 the CAD component which is valuated was the “piston”. It was important to number the protocol of the Use Cases to allow the single protocols to be matched to the related cases. In addition formal information like the date of the measurement and designers who were involved in the evaluation process has been included. The second part of the measurement protocol contained information about the parameters and associative relationships which should be evaluated. That means that the designers in each group (Group 1: Designers working with the PARAMASS approach and Group 2: those who worked without the approach) had the task to identify, determine and present the parameters and associative relationships.

Related to the evaluation of the piston the designers of each group had the task to identify geometrical parameters like: the piston diameter, length, compression height, bore and top land. Further information which should also be identified was physical parameters like the piston mass, material, centre of gravity and inertia tensor. In addition it was also required to identify structural design information inputs like the piston position, axis and the interface geometry of the connection rod which were necessary to design (position) the piston. In the final step the modified geometrical parameters had to be changed, to investigate the aspects related to the reusability of the created CAD components. Using the measurement protocol it was possible to record the results of the measurement process in a systematic way (Figure 68). The tasks accomplished by the test participants were ordered based on the required PA approach phases (Phase 1: identification of the parameters and associative relationship; Phase 2: structuring and creation phase; Phase 3: Modification of the parameters and associative relationships). The next section presents the final result of the quantitative evaluation process.


Use case measurement protocol
PISTON

Use case name: Identification and determination of the piston pin parameters
Use case number: 1
Level of the use case: Evaluation of phase 1 of the developed method
Date: 01.05.2009
Designer/Design group: with or without the method

	With the PARAMASS approach		Without PARAMASS approach	
Phase 1: Identification and determination of parameters and associativity	Time (Minutes/ seconds)	Task fulfilled	Time (Minutes/ seconds)	Task fulfilled
Geometrical parameters:				
The piston diameter:				
The piston length:				
The piston compression height:				
The piston bore:				
The distance of the piston top land:				
The piston compression ring grove:				
The piston diameter:				
The distance between bosses:				
The piston ring zone:				
Sum of the measured time and tasks				
Physical parameters:				
The piston mass:				
The piston material:				
The piston center of gravity:				
The piston inertia tensor:				
Sum of the measured time and tasks				
Process parameters:				
The rough part of the piston:				
The finish part of the piston:				
The position of the piston bore:				
The surface of the piston crown:				
The surface of the piston bore:				
The tolerances of the piston crown:				
The tolerances of the piston wall:				
Sum of the measured time and tasks				

	With the PARAMASS approach		Without PARAMASS approach	
Phase 1: Identification and determination of parameters and associativity	Time (Minutes/ seconds)	Task fulfilled	Time (Minutes/ seconds)	Task fulfilled
Associative relationship				
The piston position:				
The piston axis:				
The connection geometry between piston and connection rod				
The piston drawing				
Sum of the measured time and tasks				
Phase 2: Structuring and creation phase	Time (Minutes/ seconds)	Task fulfilled	Time (Minutes/ seconds)	Task fulfilled
Identify and determine the parts structure (rough part and finish part)				
Identify and determine the design information inputs				
Identify and determine the design information outputs				
Identify and determine the relevant reference geometry of the skeleton models				
Sum of the measured time and tasks				
Phase 3: Modification phase (modify the following parameters and associative relationships)	Time (Minutes/ seconds)	Task fulfilled	Time (Minutes/ seconds)	Task fulfilled
The piston diameter:				
The piston length:				
The piston compression height:				
The piston bore:				
The distance of the piston top land:				
The piston compression ring grove:				
The piston diameter:				
The distance between bosses:				
The piston ring zone:				
Sum of the measured time and tasks				
Total sum of the measured time and tasks				

Figure 68: Measurement protocol of the piston Use Case

8.4.2.3 Presentation of the final results of the quantitative analysis

After documenting the measured time values it was possible to compare the performance time of the different groups. This section will present the results of the quantitative evaluation of the different phases of the PARAMASS approach. There are a lot of aspects which have an impact of the total evaluation process. The purpose of the analysis was to demonstrate if there were any changes and improvements through the application of PARAMASS method. The results of the quantitative evaluation showed that by using PARAMASS designers are able to identify and determine the required parameters and associative relationships much faster than without any specific method. At first the total time during the creation of the PA CAD components (connection rod, piston, piston pin, cylinder head, cylinder block, oil pan etc.) was measured. In case of the piston it was possible to measure that working with the PARAMASS approach required longer time for the creation of the model (see Figure 69), whether the designer was CAD-experienced or not.

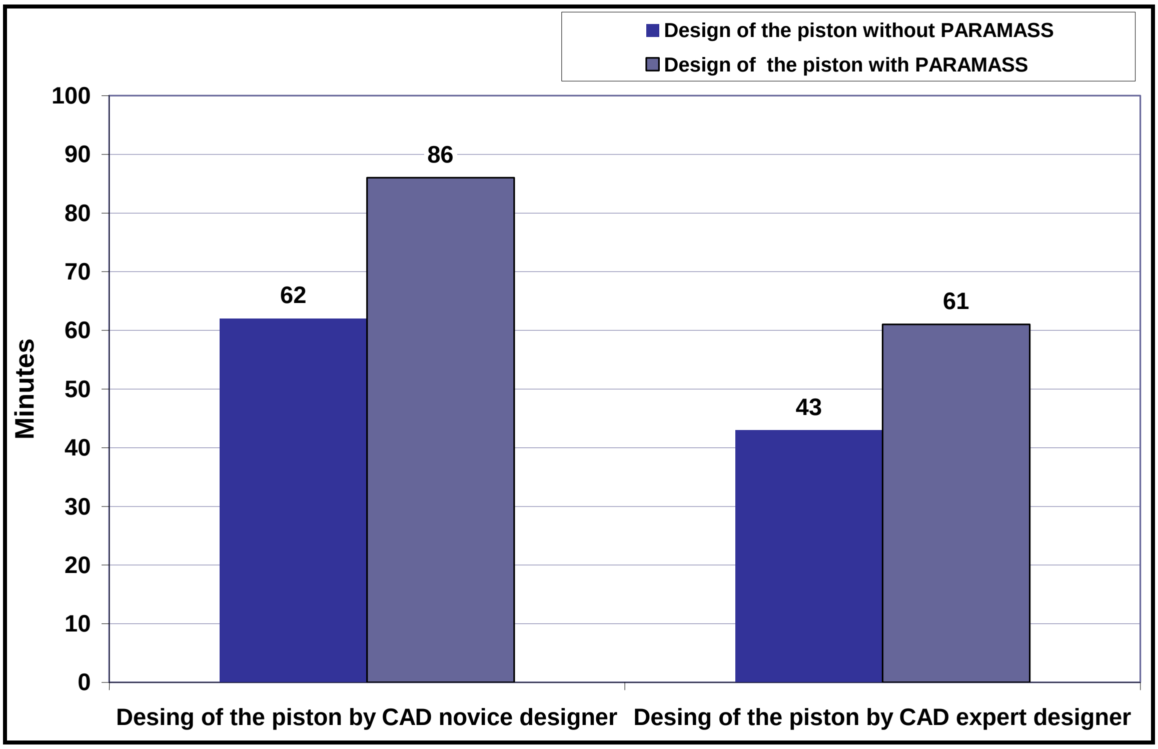


Figure 69: comparison of the creation phase with and without the PARAMASS approach

Figure 69 shows the total time of phase I the PA creation phase. The reason for the increase in time is that the designers who worked with the PARAMASS approach to carry out some additional work (for example the specification phase which require the application of the PSM and the ASM approach) which is necessary to apply the approach. But during the evaluation process it was very obvious that after the application of the method there are benefits related to the identification, determination, presentation and modification of the created PA components using the PARAMASS. This is one of the key aspects of the study. Many CAD designers mentioned that during the application of the

PA approach they could see that they have some effort but at the same time could "feel" that they have an understanding about what they are going to do next. In particular, the experienced PA CAD designers stated that they can recognize that they are able to handle the PA CAD system's complexity in a better way by means of the PARAMASS. They also stated that they had had "bad" experiences not working in a methodological way. That means that the consequences of "poor" modelling with PA CAD systems are in some ways very painful. In some cases a full new modelling of their CAD parts was necessary. Figure 70 demonstrates the results of the measured time during the identification and determination of the different kinds of parameters of a piston designed with and without the PARAMASS approach. The whole evaluation of the available components can be seen in Appendix IV.

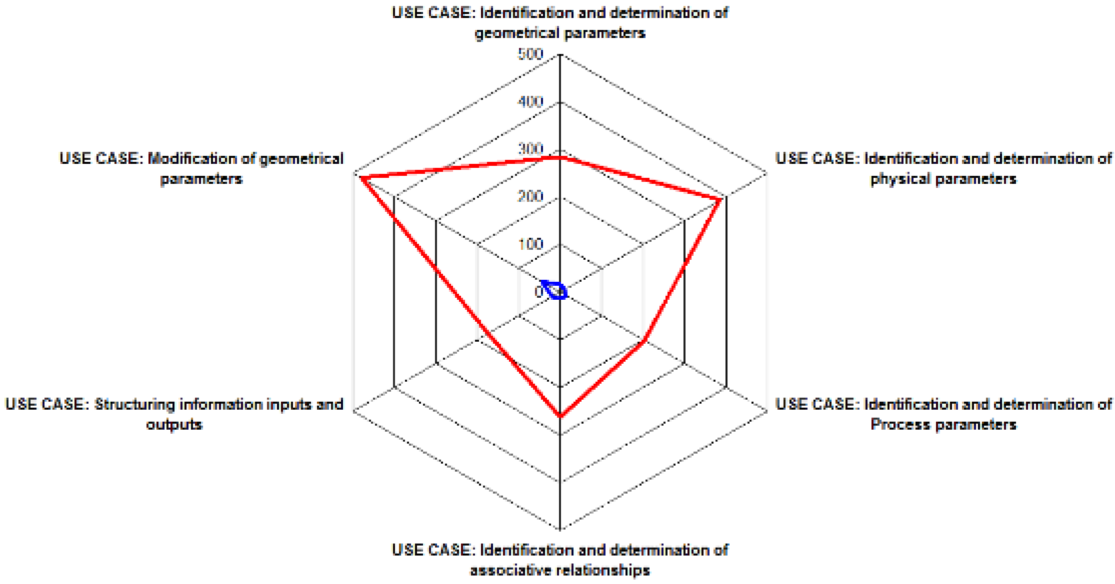


Figure 70: Total time measured during the identification and determination of parameters

During the consideration of the measured time it is interesting to see how fast the designers were able to identify and determine the required parameters. The reason is that depending on the complexity of the created CAD parts most designers have enormous problems to identify and determine the required information created by other CAD designers and colleagues. Furthermore, related to the reusability of the created PA CAD components, the designers needed a lot of time to be able to understand the design content of the created PA CAD parts without a PARAMASS approach. For a better explanation of the differences of the created CAD models with and without the PARAMASS approach

Figure 71 will be used. On the left side it is possible to see a PA CAD part which is designed with the PARAMASS approach.

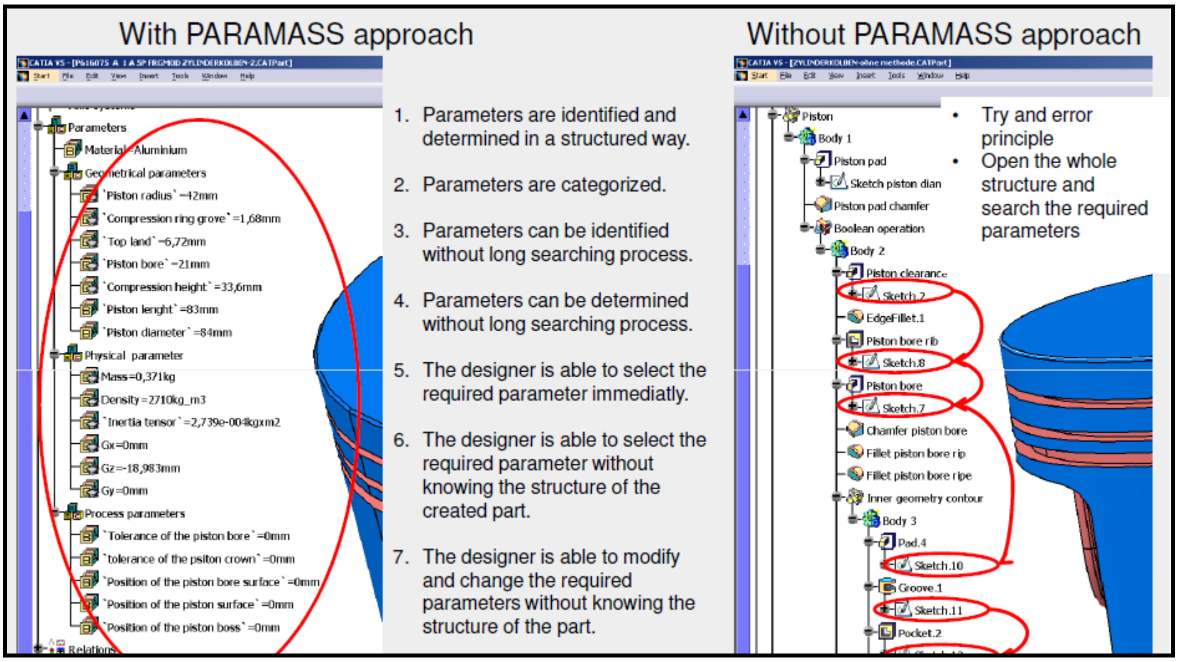


Figure 71: Comparison of the designed piston with and without PARAMASS

The left side of the Figure 81 demonstrates the significant difference between working and not working in a methodical way. The relevant parameters which have been determined by means of PARAMASS can be easily identified and the relevant parameters are presented in a very structured way. This aspect helps ensure that the relevant parameters are immediately editable and CAD designers do not need a long time to search for then. During the observation of the designers it was also possible to observe that people who are not the creator of the PA CAD components can modify the parameters without knowing the whole structure of the created features and parameters. This is a very important aspect related to the reusability of the created CAD parts and assemblies. In the past it was possible to observe how difficult it was to select and find relevant parameters. But by means of the developed approach this information can be identified more quickly. This is also the point where the designers realize the real benefit of methodical working with PA CAD systems. Especially in the power train development most of the CAD components are developed with external partners. Therefore such methodical information should be available for the development partners so they are also able to have a certain “guidelines” to design their PA CAD components.

The right hand of Figure 74 demonstrates an example of a PA CAD piston which is not created in a methodological way. It can be seen that the history tree of the CAD components contains the features and the parameters of the created piston. It is not possible to see quickly the relevant parameters and associative relationships, which makes the search of the required parameters difficult. The designers have to investigate the whole history tree to find the right parameters and the relationships between them. By means of methodical working the CAD designers were able to define the parameters (geometrical, process and physical parameters) required in the design process. Furthermore with the PSM approach it was possible to determine and cluster the different parameters in the created category. The PSM approach helps designers to achieve a better understanding about the next steps. Related to relevant design information inputs and outputs it is also possible to observe that with the PARAMASS approach, especially the PAPS and PAAS methods there are also advantages. The structure of PAPS and PAAS is designed in a way that designers have the possibility to put the design information inputs and outputs in the created place holder of such information. Figure 72 shows the PAPS which have been realized during the design process of the PA CAD components. Furthermore it demonstrates the created

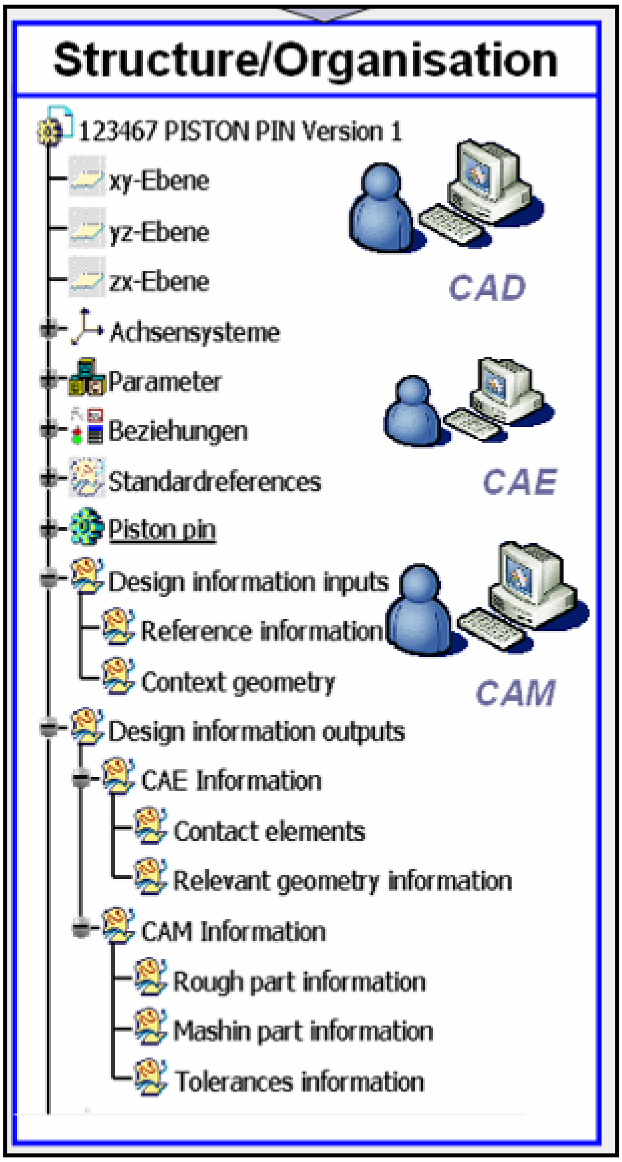


Figure 72: PAPS approach of the piston pin

Fixed structure of different information categories which are relevant for the design process partners. This means that CAE and CAM designers are now able to identify the right parameters from inside of the structure. That means they exactly know where the relevant parameters are available. The category ‘design information outputs’ is divided into CAE and CAM information and by means of strong interaction with the CAD designers the relevant parameters can be offered in a systematic and structured way. Further advantages are that downstream process information can be organised in an automatic way. That means that other systems (CAM or CAE systems) can be connected with the predefined structure. In this way the CAE and CAM systems can be adopted to the area where the relevant information is available. By means of adopting CAE and CAM engineers are able to update their latest information automatically. In case of the piston there is some information like the rough part, which is the input of the finished parts that is necessary and has to be provided to downstream process partners. Further information like the surfaces which are machined is also required as output information. Figure 73 demonstrates the time which was necessary to identify the parameter information inputs and outputs. In this case it is possible to demonstrate that by means of the method the designers were able to identify the information faster.

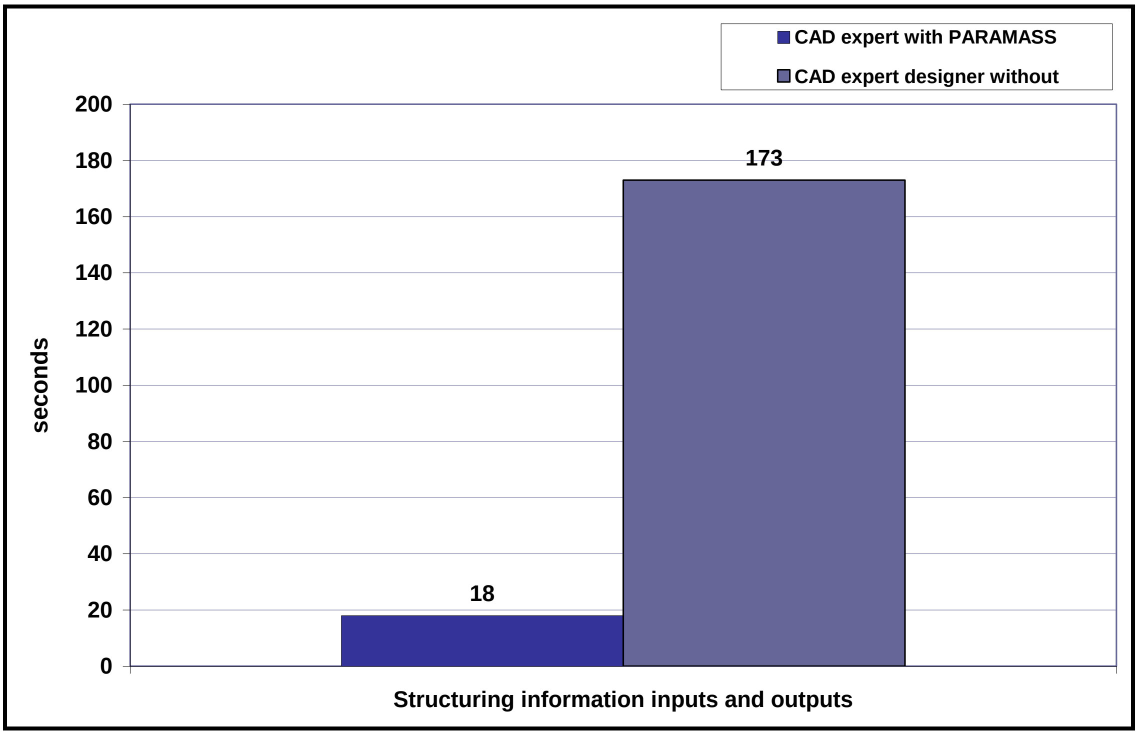


Figure 73: Measured time of the structuring aspects of the approach

Considering phase 3 the modification of the created PA CAD components, it was possible to observe that there are also advantages during the application of the developed approach. Figure 74 demonstrates the results of a study in the modification phase. Here it is quite important to say that time required for modification of parameters is closely related to the time required for identification of the parameters to be modified.

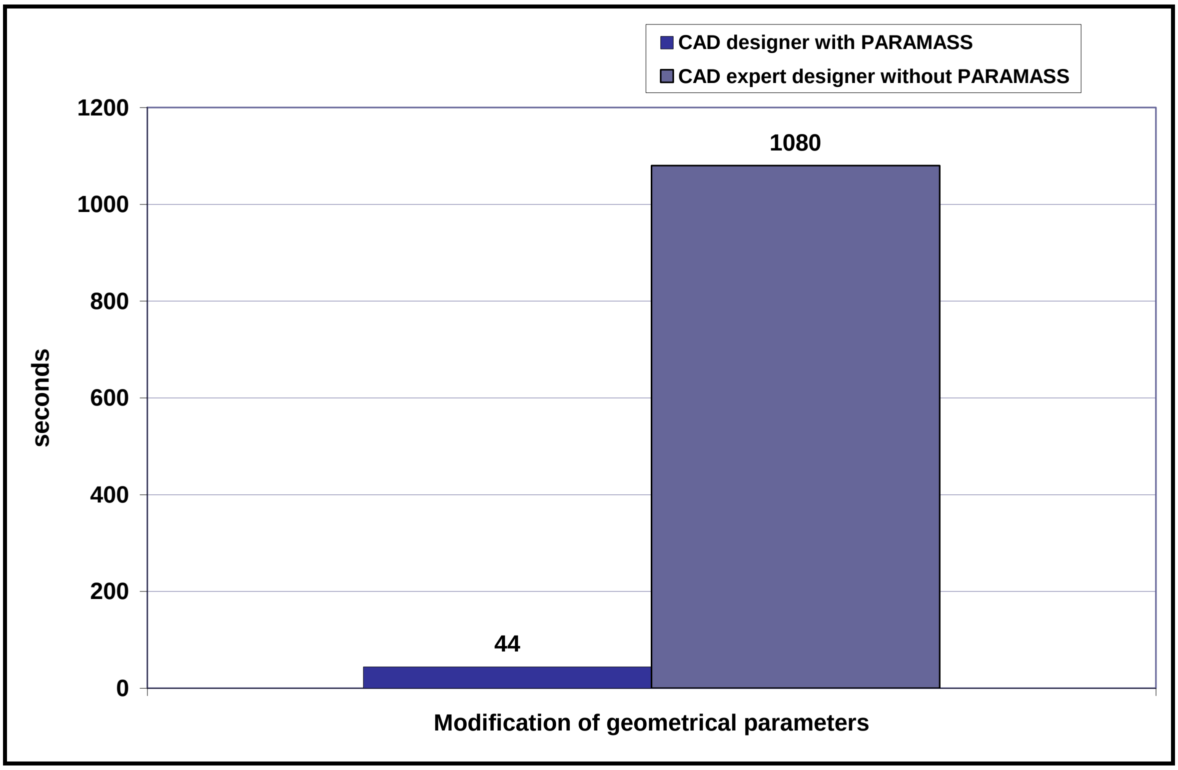


Figure 74: Measurement of the modification phase

8.5 Conclusion

This chapter has presented the evaluation of the developed PARAMASS approach. The target of the Descriptive Study II was to evaluate and investigate the changes achieved by the developed approach. It was intended to demonstrate if there are any changes through the application of the approach. Furthermore, important factors which have been identified in the Descriptive Study I (identification, determination, representation and modification of parameters and associative relationships) were evaluated. The intention was not to demonstrate the total benefit of PA systems. The evaluation process was only developed to measure the performance of the PARAMASS approach. For those reasons two different approaches of qualitative and quantitative evaluation were developed. The qualitative evaluation process was based on the Goal Question Metric (GQM) method which contains questions related to the identified factors. The results of the qualitative evaluation showed that designers have advantages related to the reusability aspects like learning, application and acceptance of the developed integrated approach. The key factors related to the reusability aspect were that the approach contains only three phases and the procedure of the developed approach was well known by the designers. The quantitative evaluation of the developed PA data was based on the Use Case approach. By means of this approach it was possible to measure the quantitative performance of the created parts and assemblies. The results of the Use Case measurements demonstrated very good advantages in the application of the developed approach. The results also demonstrated the performance and significant improvements of the developed PA approach (for example it was possible to reduce the time during the application of the method→ see figure 74). While it is quite difficult to say that the developed approach will bring a certain percentage of benefit overall, it can be said that because of the application of the developed approach designers were able to find the required parameters in a better way. It was also possible to learn that the evaluation process of the PARAMASS approach was of the most challenging parts of the research, and should be prepared very carefully. It was important to identify how, what and who exactly should be evaluated. The evaluation processes needed to be prepared with the designers who are engaged in the evaluation process. By means of involving the designers it could be ensured that the right “things” can be evaluated - appropriate CAD components, parameters and also associative relationships. The designers are the experts who exactly know the nature of their PA CAD components and they can support the researcher during identification of parameters and issues which should be evaluated. Otherwise there is a big danger that the whole evaluated CAD parts and components are not considering the important aspects like time and performance of the created PA components. Furthermore there is a long planning phase of such evaluation process in an industrial context necessary. Related to the following work the evaluation process took place over six months and this should be considered by the researcher. Another important aspect is also that the accurate documentation of such evaluation process is necessary. That means there should be an “evaluation protocol” available to help store and catch the evaluation results. Otherwise it will be quite difficult to compare the results of the evaluation process. Furthermore it should be ensured that the groups of designers who will be evaluated are well defined. That means it is quite important to elaborate the profile of the designers during the evaluation process.

9 Conclusion

The research undertaken addressed four key elements. The first one was the identification of problems, issues and important factors which have been considered during the literature survey and extended fields of studies like carrying out a questionnaire, interviews and investigation of existing PA CAD parts and assemblies in a “real” industrial context by means of action research. The second key element was the development of a new approach called PARAMASS which was based on the findings in the previous step. The PARAMASS approach was developed and applied in an automotive company which is unique because having the possibility to do such a kind of research in a company. The third key element of the work contained and discussed the problems and issues during the implementation of the PARAMASS approach in the automotive company. The final key element was the evaluation of the impacts of PARAMASS. The big contribution of the work can be seen in the last three key elements, and especially in that it was possible to show the evidence of necessity of PARAMASS approach and also the evidence of the impacts during the PARAMASS implementation and evaluation. Now in this section of the work the important findings and contribution of the work will be summarised. For a systematic accomplishment of the research work the Design Research Methodology (DRM) according to Blessing and Chakrabarti was selected. The DRM is based on different steps which are a) Descriptive Study I b) Prescriptive Study and c) Descriptive Study II.

As mentioned before the first key element was the definition of the problems and issues related to PA CAD design, identified by carrying out a literature survey and field studies. From the authors point of view the problems related to PA CAD design can be categorised into four different aspects. These aspects are: (1) the consideration of a “pre-CAD” phase which is necessary to be aware about the creation of possible parameters and associative relationships. (2) The functional aspects which contain the parameters and associative relationships itself during the “creation” of such elements. That means how is it possible to identify and determine the different kinds of parameters and associative relationships. (3) The consideration of structural aspects of PA CAD modelling which is necessary to structure the PA design information inputs and outputs. The last aspect (4) was related to the process which means of which downstream process PA design information was considered. During the literature survey t was possible to identify that three important works were related to PA design (works from Mendgen, Schenke and Forsen). All these works contained in general overall statements about the above mentioned aspects but there were gaps in all this work concerning the “methodological” consideration of how to design with PA CAD systems. All these works doesn’t present any evidence and the basis of the problems. That means that it was not obvious where and how they have elaborated their results. All of the works had a strong focus of how to deal with constraints in PA CAD design. Related to the “pre-CAD” and functional aspects of PA CAD design there were in some works statements like “designers should be careful how to design parameters and associative relationships” but as mentioned before the methodological aspect of such issues was missing. The issues related to “structural” and “process” aspects were completely missing in the studies. Furthermore none of the works had an industrial background and therefore this can also be seen as an extra contribution of the work presented here. The field studies of Descriptive Study I presented in this thesis have the target to check the findings of the literature survey but also to generate a new contribution of knowledge related to the “structure” and “process” of PA CAD design. For the accomplishment of Descriptive Study I different approaches were selected to analyse the application of PA systems in an industrial context. These approaches were combined with the study of the relevant literature, carrying out a questionnaire with 153 power-train engineers, interviewing PA CAD trainers and the investigation of 174 PA parts and assemblies. For example, related to the “Pre CAD” aspect the results of the questionnaire showed that 67% of the respondents think that it is important to understand the different kinds of parameters and associative relationships before starting to design with PA CAD systems. From the functional aspect the results of the questionnaire also showed that 76% of the designers had problems to identify the right parameters and 81% had problems to identify the associative relationships. The results of the interviews and investigated PA CAD parts confirmed also these aspects of weaknesses. Related to the “structural” and “process” aspects it was possible to identify that 68% of the respondents had problems to structure their own PA CAD parts and assemblies. This point was also confirmed after the investigation of existing PA parts assemblies. According to the complexity of the investigated parts only 24% of parts with low complexity were structured and only 11% of the parts with a high level of complexity were correctly structured. This point showed the enormous problems in addressing the “structural” aspect of the PA components.

There were also significant weaknesses related to the "process" related aspect. The results of the questionnaire showed that most of the designers are not able to find the right parameters and relationships. The investigation of the analyzed PA parts and assemblies showed that in only some parts some process related information were available.

The second key element was the development of the PARAMASS approach for tackling the problems from Descriptive Study. PARAMASS contained three upper level steps (1) the specification phase (2) the structuring/creation phase and (3) the modification phase. By means of the specification phase it was possible to tackle the problems related to "Pre-CAD" and "functional" aspects. That means this phase helped designers to prepare, understand, identify and determine the relevant parameters and associative relationships. Furthermore the specification phase offered two newly developed approaches to assist in organising and structuring parameters and associations which were the PSM and the ASM approach. These new and innovative approaches helped designers to have a method to identify, define and determine the different kinds of parameters and associative relationships. The next step of PARAMASS, which is the "structuring/creation phase", tackled the problems related to the "structuring" and "process" aspects. Especially for this phase two new developed approaches, PAPS and PAAS, have been successfully generated. By means of these two new approaches it was possible to use pre-defined structures for CAD parts and assemblies. The advantages of these two approaches were that for all of the design participants a common "standard" of the PA part structure was available. That means that the PA design participants and process partners know exactly where the PA design information is structured and available. In a "real" industrial design environment this step can be seen as a big contribution in offering PA design standards inside and outside the company.

The third key element of the work concerned the issues related to the implementation of the PARAMASS approach in an industrial context. In this respect it was possible to generate new knowledge about the integration and implementation of the PA design method in the industrial context. It was possible to observe that during this phase the following aspects are important for the designer: (1) the designers need to be involved and informed; (2) the targets of the planned project and activities have to be clarified; (3) the designers should have a voice in the planning of the PA method; (4) the management should support the PA method; (5) the management should procure the designers time for training.

The final element of the presented work was the evaluation of the developed PARAMASS approach in Descriptive Study II. The target of this study was to evaluate and investigate the changes achieved by the developed PARAMASS approach. It was necessary that important factors which have been identified in Descriptive Study I (identification, determination, representation and modification of parameters and associative relationships) should be able to be evaluated. The intention was not to demonstrate the total benefit of PA systems. The evaluation process was only developed to measure the performances of the PARAMASS approach. For those reasons two different approaches of qualitative and quantitative evaluation were developed. The qualitative evaluation process was based on the Goal Question Metric (GQM) which contains questions related to the identified factors. The results of the qualitative evaluation showed that designers have advantages related to the reusability aspects like learning, application and acceptance of the developed integrated approach. The key factors related to the reusability aspect were that the approach contains only three phases and the procedure of the developed approach was well known by the designers. Furthermore the PSM and the ASM approaches were easy to learn and there was not much training necessary to learn the idea behind the two approaches. The designers also evaluated the PAAS and PAPS approach as a good method. In this way designers indicate that their required PA information is stored in predefined placeholders and because of that they know exactly where they can find the required data. The quantitative evaluation of the developed PA data was based on the Use Case approach. By means of this approach it was possible to measure the quantitative improvement in performance in the creation and modification of parts and assemblies. The results of the Use Case measurements demonstrated good advantages in the application of the developed approach. The results also demonstrated the performance improvements of the developed PA approach. Therefore it is quite difficult to say that the developed approach will bring a certain percentage of benefit. But it can be said that because of the application of the developed approach designers were able to find the required parameters in a better way.

Related to future works it is quite important to find approaches which are able to integrate the created parameters and associative relationships inside the Product Data Management

(PDM) and Product Lifecycle Management (PLM) approaches of engineering companies. Furthermore there are also approaches necessary of how to manage and deal with the created data and information related to the PA approach. Therefore the created information of the developed PA parts and components must be implemented and integrated in the current systems and IT environment. Further issues are the integration of the suppliers in the method application and development. That means that the method should be embedded in standards used during the design process - different PA design standards and method modules should be developed for the different areas of the PA design methods. Another significant contribution for the future is the transformation of the developed PARAMASS approach to other domains. This means it would be very interesting to research if the developed approach and its defined phases can be applied in other sectors like aerospace industry. Furthermore there will be a contribution that the idea of PSM or ASM approach can also be transferred to other component design areas. This possibly would open another gate and dimension for design research and community.

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Glossary

The following section describes the terms which are used often in the following thesis. Furthermore these definitions should help readers to have a clear understanding of the used technical terms.

Assembly: An assembly is a number of parts or subassemblies which constitute a unit in some sense (design, configuration etc.). An assembly generally has a part number assigned to it for identification [AIT, 1995].

Associativity: Related to design process associativity is the fixed relationship and connection between geometrical entities and objects. These associative relationships include also the connection of 3D models and down stream process related elements. The parametrization of a 3D model (feature) implies the parametrization of derived information items of this 3D model (feature) that are a result of other applications (draft projections with dimensions or the numerical control programme for the previous examples). By these means, any modification in a 3D model (feature) is automatically propagated to down-stream applications and connected geometries [AIT, 1995].

Attribute: Attributes are used to define the static characteristics of an object (e.g. an engineering element).The "static characteristic" means a property which may be expressed by one or more values as opposed to a time depended behaviour ("dynamic property") [VDA, 2002].

Characteristics: It describes the product's structure and shape and can be directly determined by the designer. For example shapes, dimensions, materials, product structure etc. [WEBER, 2007].

DMU: Digital Mock-Up (DMU) is a realistic computer simulation of a product with the capability of all required functionalities from design/engineering, manufacturing and product service environment which is used as a platform for product and process development, for communication and decision from a first conceptual layout to maintenance and product recycling [AIT, 1995].

Feature: Features represent the engineering meaning or significance of the geometry of a part or assembly [SHAH AND MÄNTYLA, 1995].

Function: Relationship, described without regard to the solution, between input, output and state variables of a systems [VDI, 2223].

Geometric Model: A geometric model is a representation of a shape. The geometric data are typically generated by CAx systems in digital form [VDA, 2002].

Method: Systematic approach to achieving a certain goal [VDI, 2223].

Methodology: Systematic procedure including several methods, tools and instruments [VDI, 2223].

Modelling: Preparing the three dimensional geometry of form design elements with 3D CAD systems [VDI, 2223].

Object: Object is anything, real or abstract, about which we store data and those methods that manipulate the data. An object is an instance of an object class [VDA, 2002].

Parametric systems: parametric systems solve constraints by applying sequentially assignment to model variables, where each assigned value is computed as a function of the previously assigned values. Unlike procedural systems, the order of the assignment is flexible, determined by a constraint propagation algorithm [SHAH AND MÄNTYLA, 1995].

Part: Parts are those elementary objects from which an industrial product is composed, where each one of these objects is manufactured by an independent process. A part is not composed by other parts [VDA, 2002].

Product Model: A product model means a computer stored model of a part, an assembly or a complete product containing all information necessary for development, manufacturing and maintenance [VDA, 2002].

Product structure: Product structures are based on abstract/logical/generic/conceptual product components or functions, which each serves as a "placeholder" for one or more physical components (technical solutions). Abstract product structures usually contain configuration information (specifications and configuration rules) [AP214 CC8].

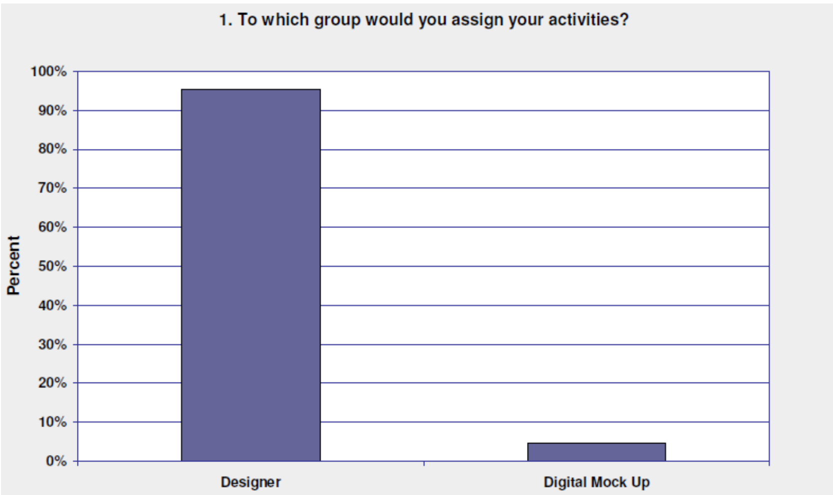
Product: It is the result of development and design process and it can be manufactured [VDI, 2223, page 90]. A product can be sold to a customer. Examples for products are passenger cars, commercial vehicles/trucks, busses, engines or other components of these products (gear boxes, chassis, engines, cabs, axles etc.) [VDA, 2002].

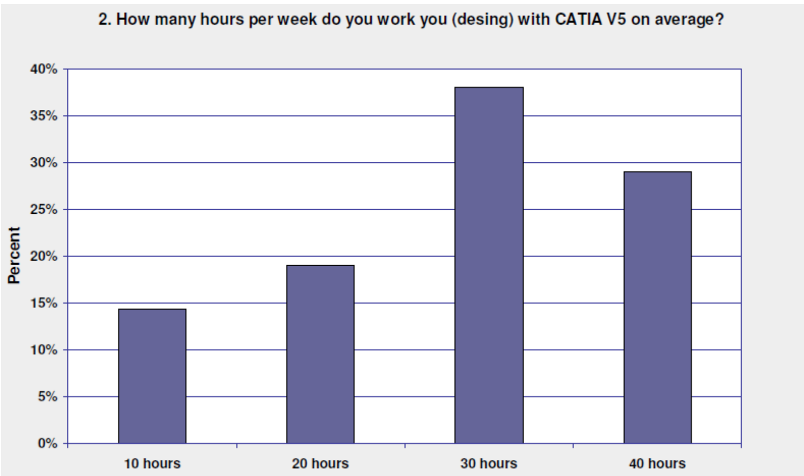
Requirement list: Written compilation of the requirements imposed on a product [VDI, 2223].

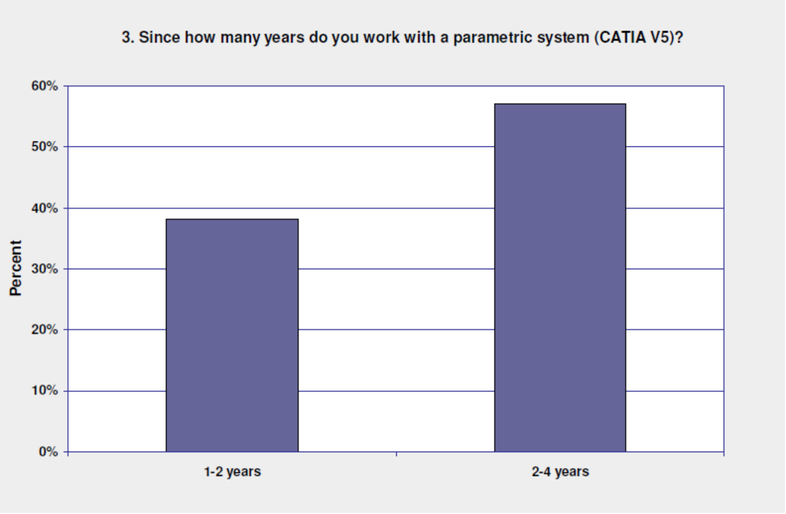
Requirement: Qualitative or quantitative desired property of the product to be developed [VDI, 2223].

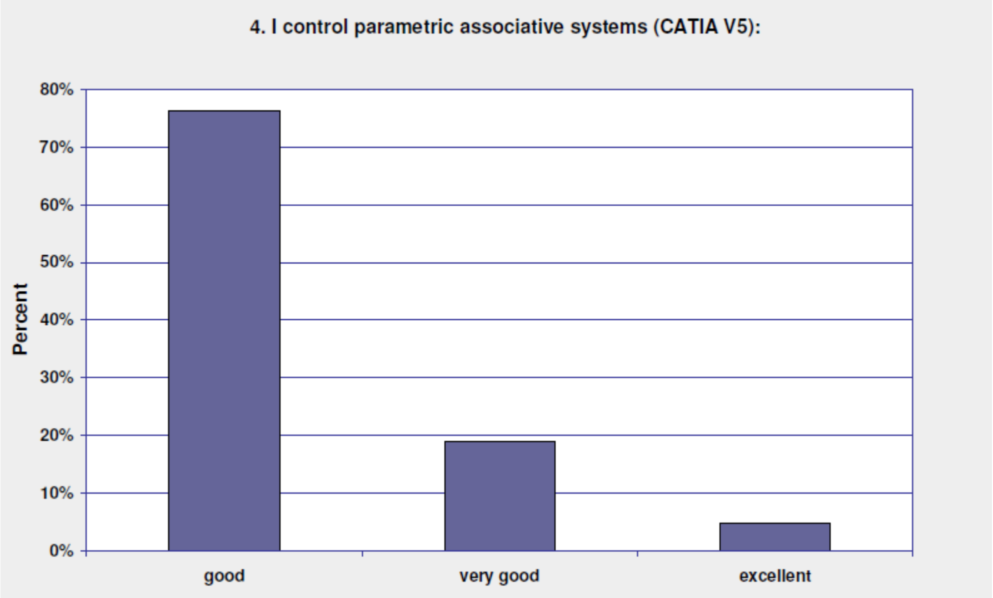
Appendix I (Results of the questionnaire of Descriptive Study I)

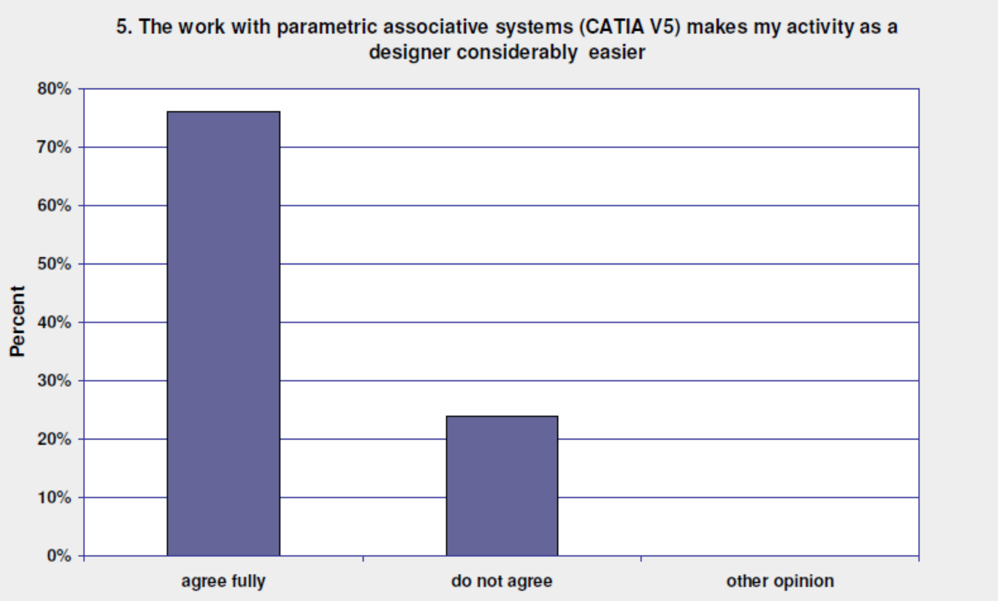
This section of the work presents the questions which have been asked during the Descriptive Study I. These questions have been asked in an industrial context in an automotive company. The purpose of this questionnaire was to elaborate findings related to the work with PA CAD systems. In the carried out questionnaire 153 power train designers from an automotive company have questioned. They had 90 minutes to answer the questions and the questionnaire was included in the content of workshops related to PA design methods. In this case it was ensured that designers answered all the asked questions. The preparation and accomplishment of this questionnaire took place between the April-October 2009 and during this time the researcher was able to accompany the designers during this stage.

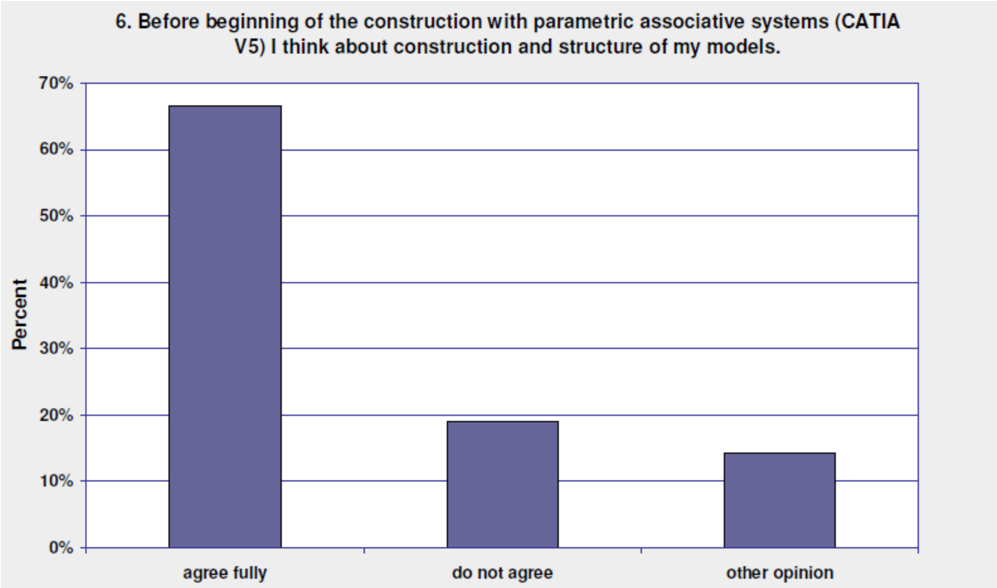


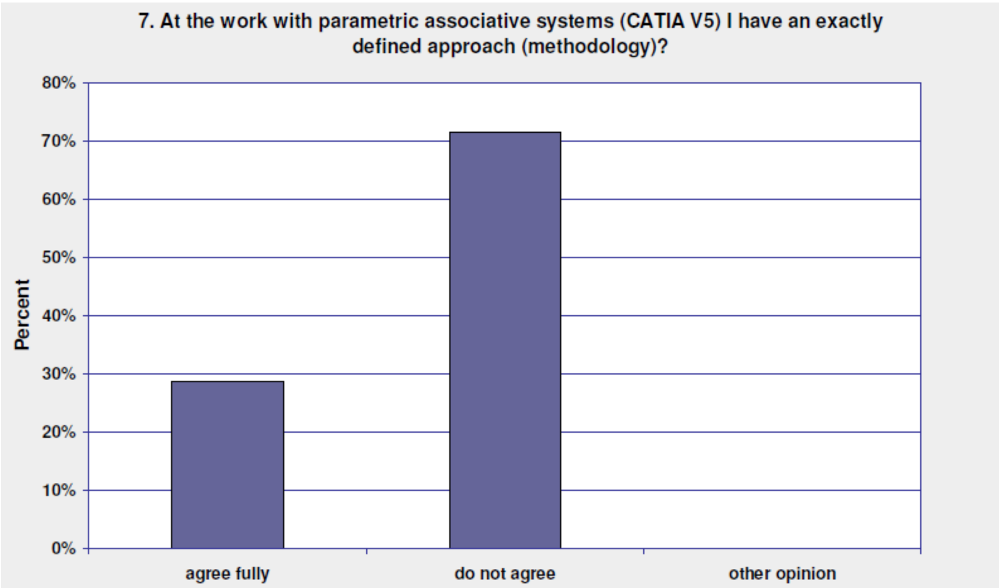


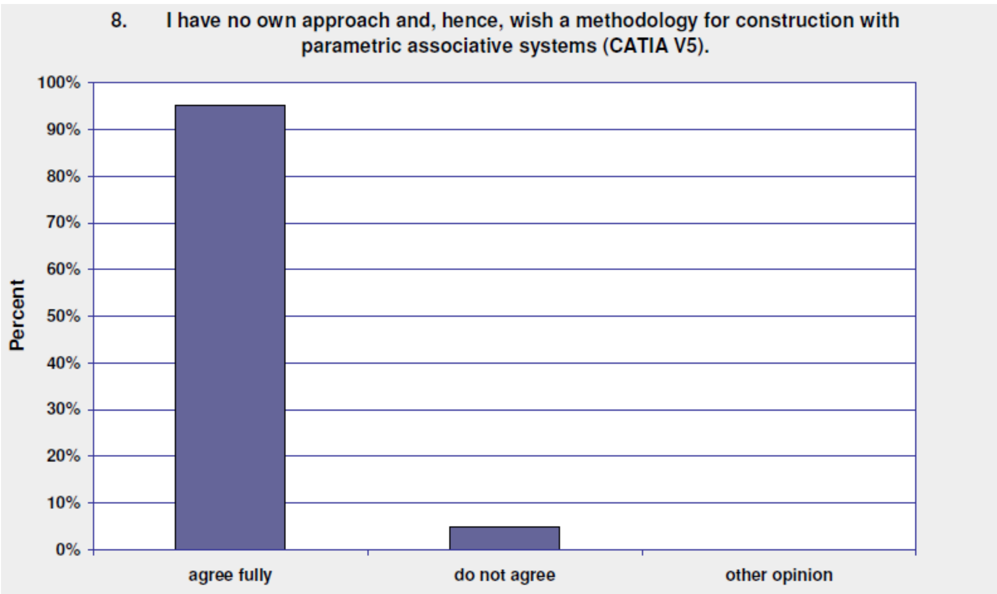

3. Since how many years do you work with a parametric system (CATIA V5)?
Percent
60%
50%
40%
30%
20%
10%
0%
1-2 years
2-4 years

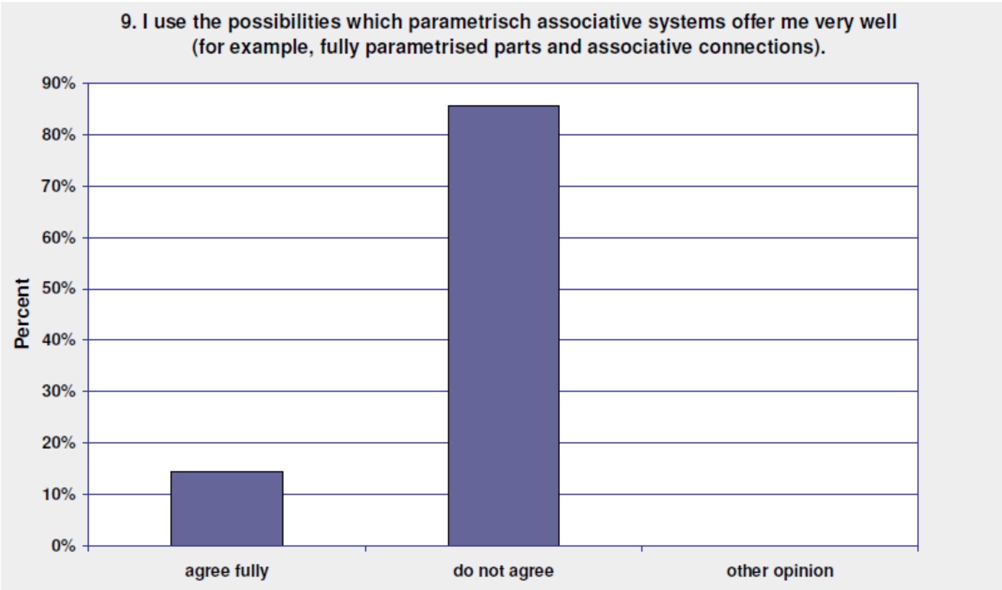

4. I control parametric associative systems (CATIA V5):
Percent
80%
70%
60%
50%
40%
30%
20%
10%
0%
good
very good
excellent

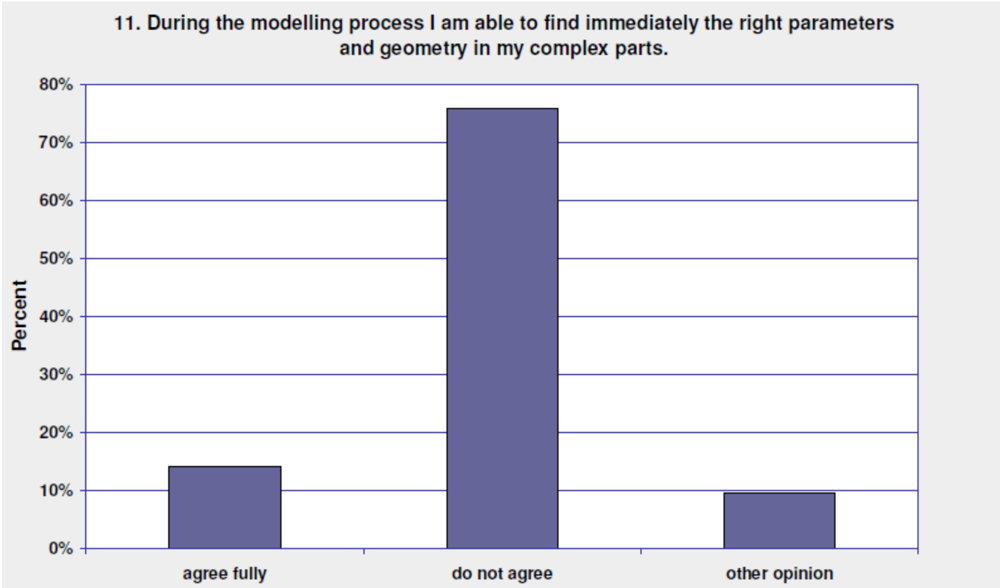

5. The work with parametric associative systems (CATIA V5) makes my activity as a designer considerably easier
Percent
80%
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion

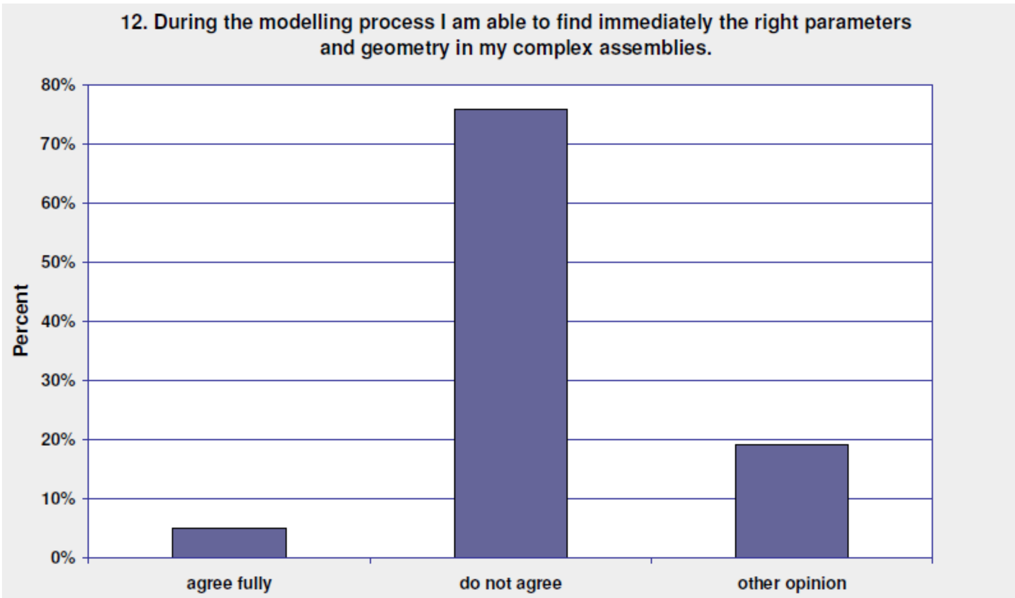

6. Before beginning of the construction with parametric associative systems (CATIA V5) I think about construction and structure of my models.
Percent
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion

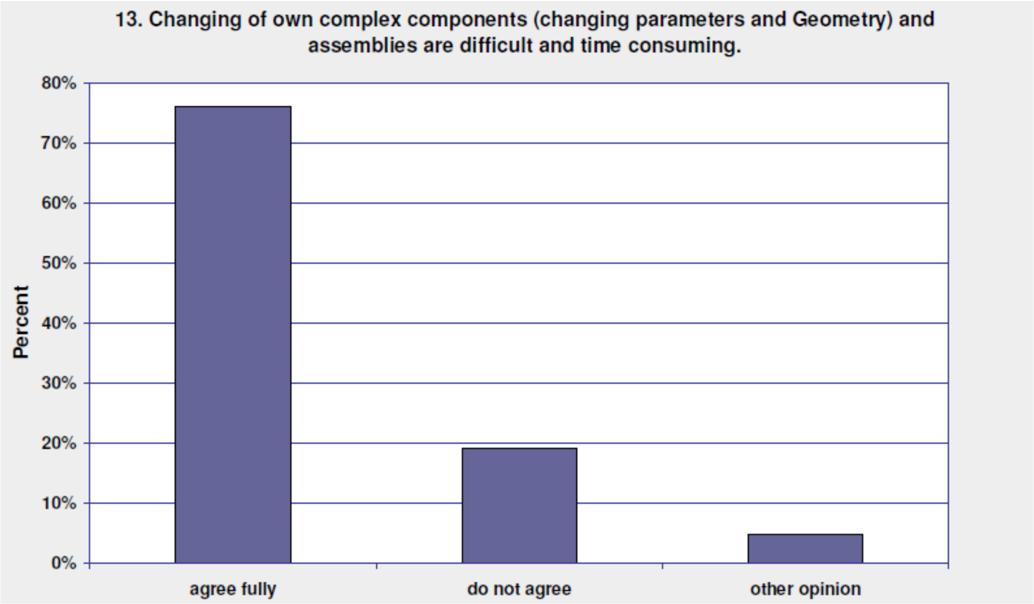

7. At the work with parametric associative systems (CATIA V5) I have an exactly defined approach (methodology)?
Percent
80%
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion

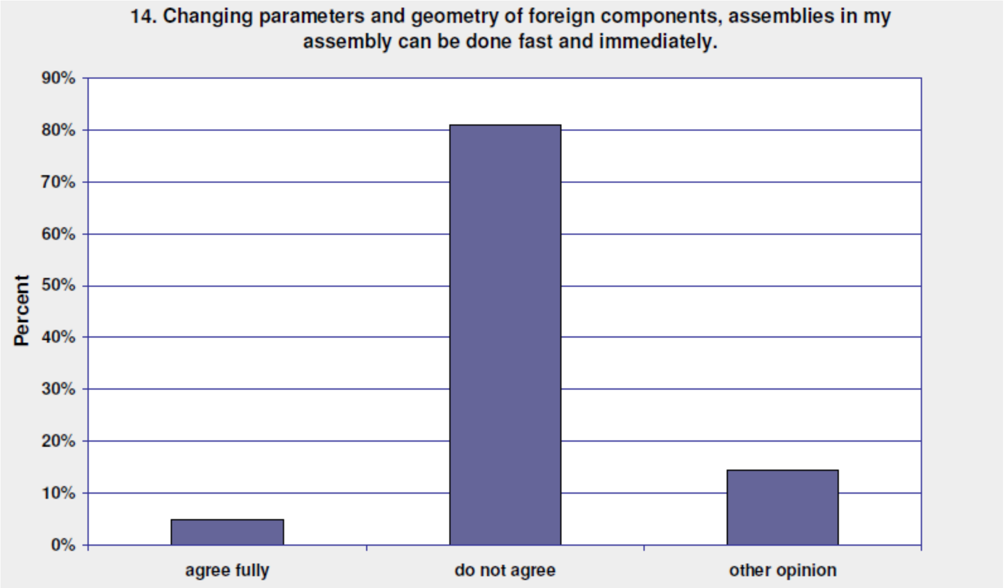

8. I have no own approach and, hence, wish a methodology for construction with parametric associative systems (CATIA V5).
Percent
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion

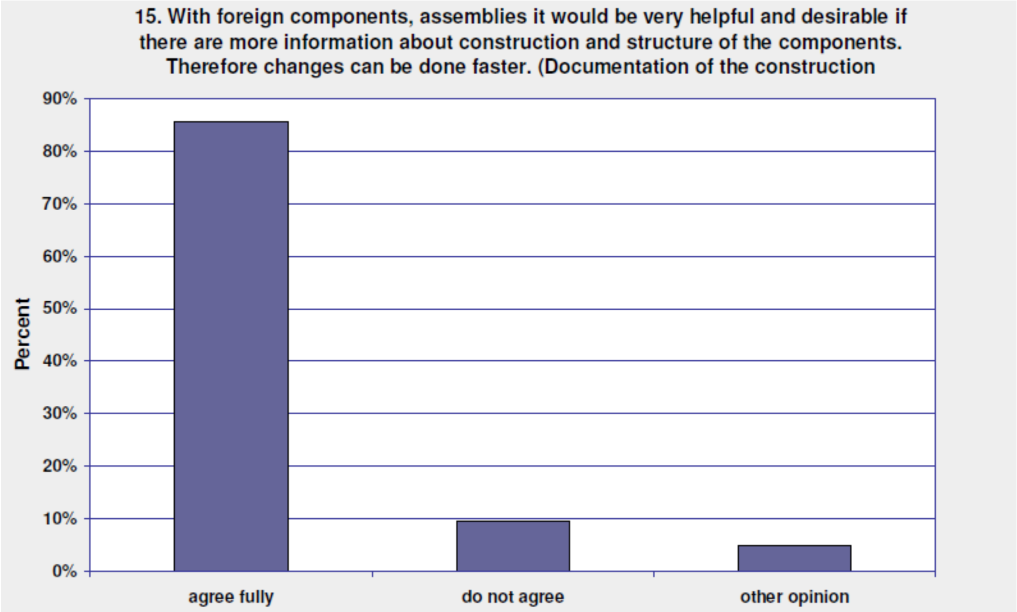

9. I use the possibilities which parametrisch associative systems offer me very well
(for example, fully parametrised parts and associative connections).
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent
agree fully
do not agree
other opinion

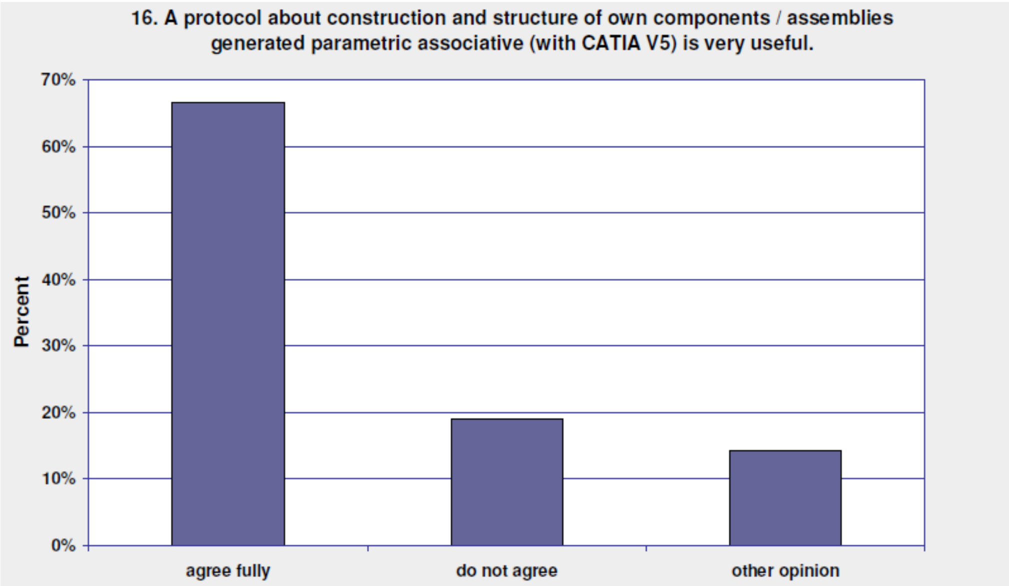

11. During the modelling process I am able to find immediately the right parameters
and geometry in my complex parts.
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent
agree fully
do not agree
other opinion

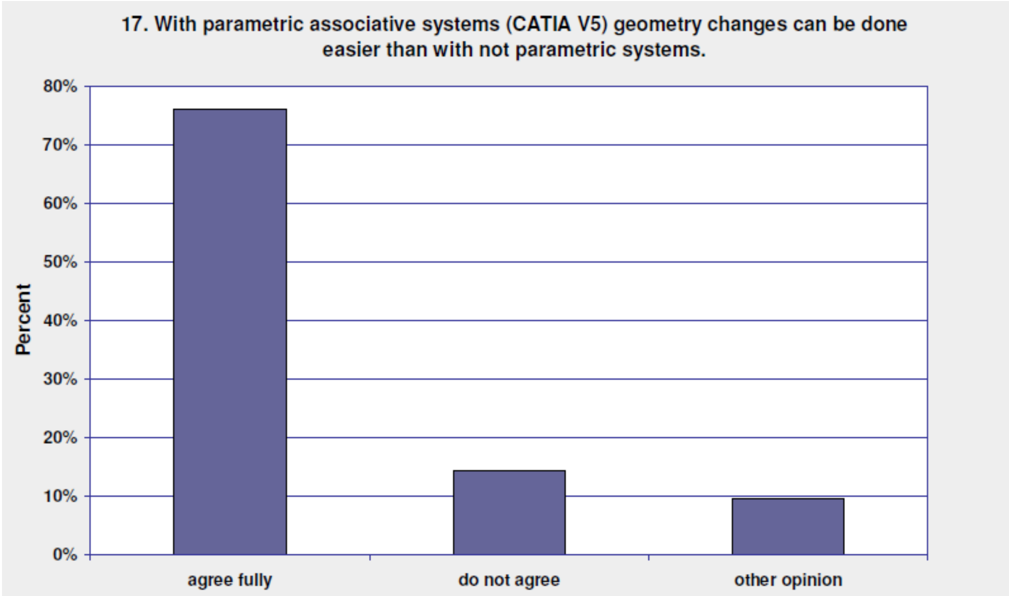

12. During the modelling process I am able to find immediately the right parameters
and geometry in my complex assemblies.
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent
agree fully
do not agree
other opinion

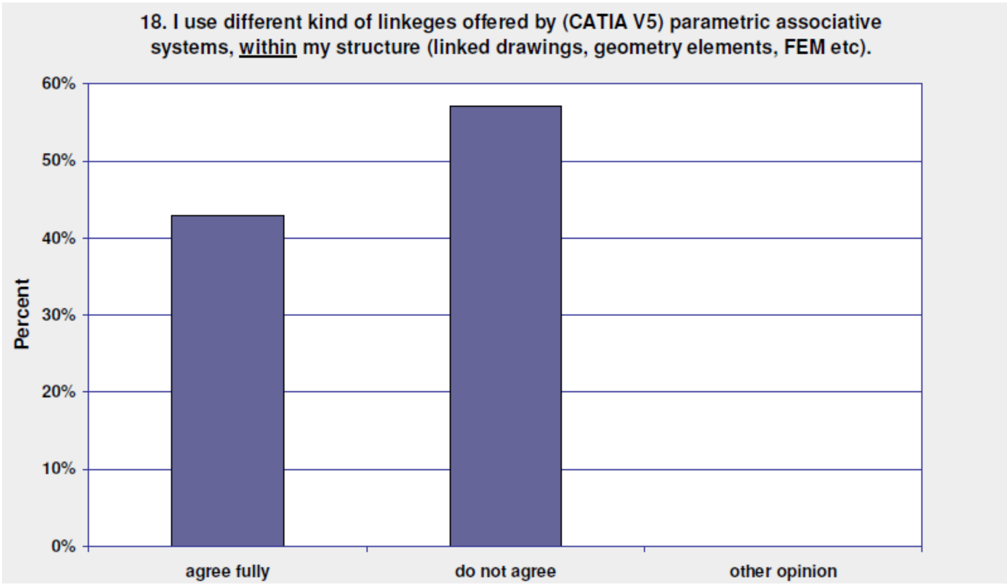

13. Changing of own complex components (changing parameters and Geometry) and assemblies are difficult and time consuming.
Percent
80%
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion

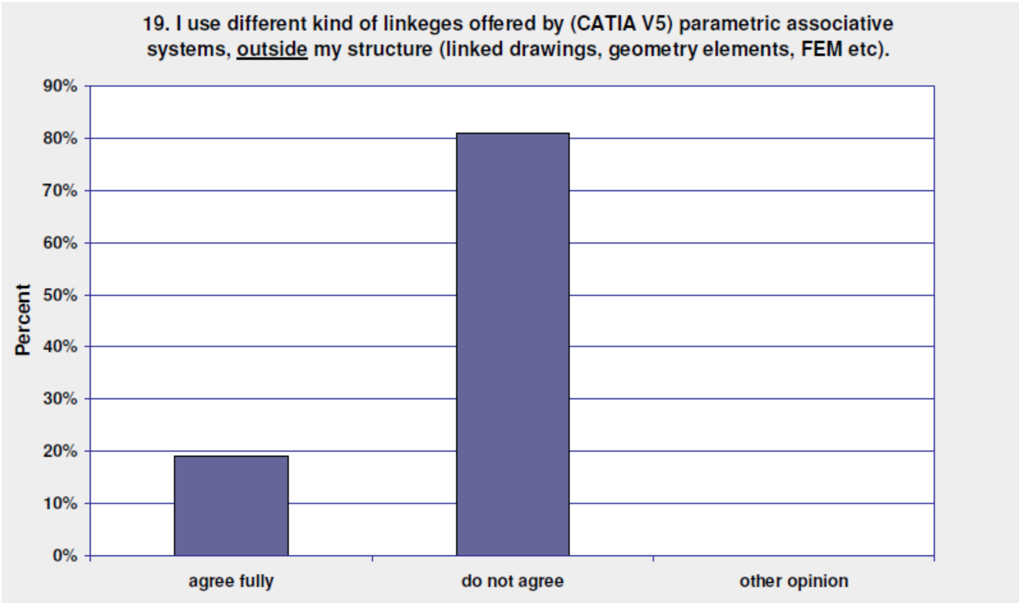

14. Changing parameters and geometry of foreign components, assemblies in my assembly can be done fast and immediately.
Percent
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion

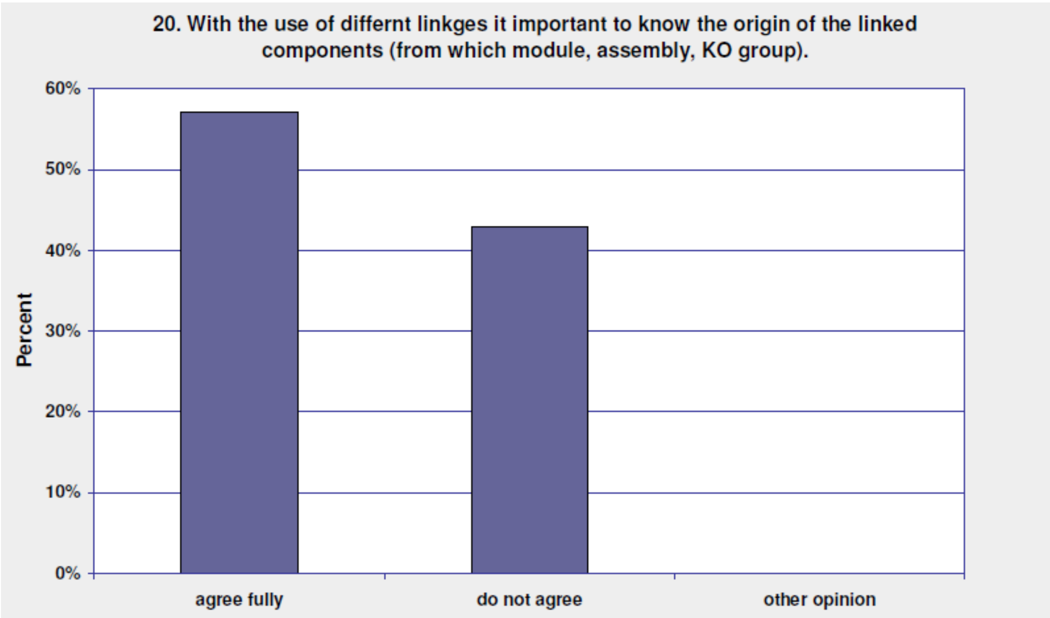

15. With foreign components, assemblies it would be very helpful and desirable if there are more information about construction and structure of the components. Therefore changes can be done faster. (Documentation of the construction
Percent
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion


16. A protocol about construction and structure of own components / assemblies generated parametric associative (with CATIA V5) is very useful.
Percent
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion


17. With parametric associative systems (CATIA V5) geometry changes can be done easier than with not parametric systems.
Percent
80%
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion


18. I use different kind of linkeges offered by (CATIA V5) parametric associative systems, within my structure (linked drawings, geometry elements, FEM etc).
Percent
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion


19. I use different kind of linkeges offered by (CATIA V5) parametric associative systems, outside my structure (linked drawings, geometry elements, FEM etc).
Percent
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion


20. With the use of differnt linkges it important to know the origin of the linked components (from which module, assembly, KO group).
Percent
60%
50%
40%
30%
20%
10%
0%
agree fully
do not agree
other opinion

Appendix II (Results of the interviews):

In the Descriptive Study I the researcher interviewed 11 CAD trainers who work very closely with the designers. The intention of the researcher was to get more information about the work of the designers with PA CAD systems. In this section only two of the interviews have been translated from German to English. (The other interviews are available in electronic in German language).

Interview partner 1:

Current position: Mr. Roland S. is responsible for the integration of methods at a European automotive company.

Work Background: More than 7 years work experience with a PA design system (CATIA V5).

1. **What is the challenge for the designer during the work with a PA design system?**

   The greatest challenge and the most important point is to keep a clear view of all dependencies during the design process. The designer has to make decisions which have no technical or engineering aspects but are rather related to the internal and logic aspects of design (process). Later geometrical changes have to be analysed and clarified. The designer must have some "foreseeing" talent. The greatest challenge is to fulfil these requirements under time pressure.

2. **How does the experience of the designer affect the modelling process with PA systems (CATIA V5)?**

   This aspect can not be generalized. However young and new CAD designers are more careful, step gently and are more "well obeying" as experienced designers. Experienced designers tend to better understanding the idea of PA design and work far cleaner as inexperienced designers. Experienced designers are also more doubtful and insecure about new PA design systems.

3. **With which special difficulties are designers confronted during the design process with PA systems?**

   It is important to keep the design results created with PA design systems clear. This clearance can be seen in the historical graph of parts and assemblies. The most difficult aspect is taking over foreign parts (these parts do not belong to the designer) and assemblies. The reason therefore is that there is no documentation about the part creation history or how designers have implemented their knowledge in a PA design part or assembly.

4. **Many designers have worked with a non parametric system (CATIA V4) before CATIA V5. How does this situation affect the learning process with a PA system?**

   The results of their parts and assemblies are quite different. Many designers who worked before with a non PA system try to transfer the design logic with a non parametric system in a PA system (round about 30% of the user). But for most of them it is quite difficult to give up their old procedure and accept the new method.

5. **What is, in your opinion, the first impression of the user (designers) at the application of new methods with CATIA V5?**

   Normally they are very impressed and positive but sometimes you can hear some sceptics.

6. **Do you think that there are different methods for PA design system?**

   There are different methods and concepts. But in many departments there is not a well defined method for PA design systems. The most important aspect for developing a new method is to clarify this with the users and designers. This point affects a positive feedback of the user.

7. **Is there a recommended method during the work with PA design systems?**

   There are some principles but there is not a general method for PA design. But the most important aspect of a new method is that it should be integrated in the product development process. It is also important to clarify in which step of the process development this methods will be applied.

8. **Which aspects increase the acceptance of new design methods with PA design systems?**

   A clean description of a method and the demanded data quality is one of the most important aspects. But it is also very important to support the designer during the implementation phase of a method (strong support necessary).

9. **Which aspects are important for a “good method”?**

   → Comprehensibility of the part and assembly design.

   → Clear and simple associativities.

   → Good structuring of the historical graph.

   → Clean naming of the features, parts and assemblies.

10. **By means of which aspects is it possible to identify „good“ and „bad“ design methods?**

    By means of analysing the associativities, the structure and the naming of the parts or assemblies it is possible to use the systems best. The most important criteria are to create parts and assemblies with high geometrical change flexibility and well structured associativity chains in the product development process.

11. **Which aspects are important for a successful implementation of design methods?**

    It is very important to be honest with all the users. That means that during the method development process all the advantages and disadvantages should be communicated. The result of such procedure is that designers have trust in the project and intension. This trust tends to apply a method.

12. **How is the feeling (designer) during the creation of associativity between their geometry?**

    At the beginning designers are a little bit sceptics. But after a while they use the offered associativity.

13. **Which aspects are important during the creation of associativity?**

    During associative design it is very important that designers have time to think about their modelling strategy. Otherwise they will be lost in a net of associativity and geometrical changes will be impossible.

Interview partner 2:

Current position: Mr. Bernd K. is responsible for the method development in power train engineering at a European automotive company. He is also a trainer and coach for PA design (Pro/Engineer).

Work Background: More than 13 years work experience with PA design systems (Pro/Engineer and Pro/Intralink (PDM-System)). He started to work as a design and calculation engineer in different areas amongst others automobile, packaging and construction machines (John Deere).

1. What is the challenge for the designer during the work with a PA design system?

The challenge during the work with a PA design is to realize the dependencies between the design objects and the geometrical entities. This is very difficult at the beginning of the work with a PA system. That means designers often don’t know the existential dependency between geometrical entities. For instance sometimes they try to delete parent-elements and wonder that the children elements also will be deleted. But the biggest problem is to handle the associativity between the objects (Part and Drawing). The great challenge is "how to handle the associativity during the design process?"

2. **How does the experience of the designer affect the modelling process with PA systems (CATIA V5)?**

Generally all of the users have the following problems:

- How are the dependencies (associativities) between the geometric object?
- How is it possible to use the associativities best?
- Where are the associated parts and assemblies coming from?

3. **With which special difficulties are designers confronted during the design process with PA systems?**

One of the greatest problems for the designer is that with a PA system they have to think about their modelling process and because of the associativity between the design elements it is difficult to change or delete geometrical entities.

4. **Many designers have worked with a non-parametric system (CATIA V4) before Pro/Engineer. How does this situation affect the learning process with a PA system?**

This question can be answered with a very good example. One of our users had only experience with a non parametric system (in this case Catia V4). If you work with a non parametric system you can create and delete parametric elements very easy (there is no dependency between the geometrical elements). And if you have some changes you can delete the changing area easy and then create the geometry new. Exactly this is not possible with a PA system. But many users try to do this.

5. **What is, in your opinion, the first impression of the user (designers) at the application of new methods with Pro/Engineer?**

Normally at the beginning the designers are very enthusiastic and inquisitive.

6. **Is there a recommended method during the work with PA design systems?**

There are different methods which are in the mind of designers. The challenge is to understand the requirements of the different designers.

7. **Which aspects increase the acceptance of new design methods with PA design systems?**

Methods must be clear and easy to learn. The next important point is to show the benefits of methods.

8. **Which aspects are important for a "good method"?**

Normally at the beginning the designers are very enthusiastic and inquisitive.

In this part of the work the author will represent the results of the interview which have been done with CAD coaches and designers. In this phase experienced CAD system coaches have been interviewed. The target of the questions in these interviews was to have a clear understanding of the problems, challenges and expectations of the designers of a parametric associative CAD system. The most important aspects and results (clustering of the important issues addressed by the different interview partners) from the interviews with the interview partners) of the interviews with CAD experts and coaches can be summarized as follows:

- During the work with parametric associative systems designers have to think about possible modifications of their parts and assemblies (foreseeing talents).
- There are confronted with problems which are not related to the product but are rather related to the logical (relationships between parameters and associative geometries.
- For many designers it is quite difficult to create a design strategy of how to create their parametric associative parts and assemblies.
- The relationship between the geometrical entities and parameters are for many designers not clear enough. That means that they have not the right tools and methods to analyse and present such associative relationships. Furthermore many of them do not know how and with which geometrical entities such relationships should be created.
- Many associative relationships are created without preliminary consideration and therefore changes in later stages of product development process are more complicated.
- The parametric associative parts and assemblies are not very well structured and therefore it is quite difficult to change and to find certain information result.

The above mentioned aspects also shows that experienced CAD coaches preferring and forcing that the design process with parametric associative systems need a certain procedure and methodology to achieve better parametric associative parts and assemblies.

Appendix III (Questions related to the usability aspects and results)

These questions have been asked in an industrial context in an automotive company. The purpose of this questionnaire was to evaluate the developed PARAMASS approach in the current thesis from a qualitative and quantitative aspect. In the carried out questionnaire questions were answered by 61 power train designers from an automotive company. They had 100 minutes time to answer the questions. The questionnaire was the content of different workshops related to the application of the developed PARAMASS approach. In this case it was ensured that designers answered all the asked questions. The preparation and accomplishment of this questionnaire took place between the March-September 2010 and during this time the researcher was able to accompany the designers during this stage.

General question about designer's profile and requirements to design method

1. How much work experience do you have in your current field? ______Y/M

Goal:

Object: Testing/Experiment phase of the PA design method

Purpose: Evaluation of the acceptance, learning and understanding of the developed PA method related to the work experience of the designers.

Viewpoint: Designer

Environment: Evaluation of the Pilot project

Question: How many work experience do you have on your work field?

Metric: Determination of the influence of the work experience related to the acceptance, understanding and learning to the presented PA method.
How is the method understanding of experienced and inexperienced designer with PA design method?
How is the learning process of experienced and inexperienced designer with PA design methods?
How is the acceptance of experienced and inexperienced designer with the PA design methods?
How is the method application of experienced and inexperienced designer with the PA design methods?
How is the influence of the knowledge of experienced and inexperienced designer with the PA design methods?

2. What is your education/qualification?

☐ Vocational Training ☐ University Bachelor ☐ University Master
☐ Technician ☐ Others: _______________

Goal:

Object: Testing/Experiment phase of the PA design method

Purpose: Evaluation of the acceptance, learning and understanding of the developed PA method

related to the qualification of the designers. *Viewpoint:* Designer, *Environment*: Evaluation of the Pilot project
Question: What is your education/qualification?
Metric: Determination of the educational background related to the acceptance, understanding and learning to the presented PA method. How is the impact of the education of the PA method application?

3. How many work experience do you have with PA CAD systems? ____________Years/Month

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the acceptance, learning and understanding of the developed PA method related to the PA system experience of the designers. *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project
Question: How many work experience do you have with PA CAD systems?
Metric: Determination of the influence of the PA system experience related to the acceptance, understanding and learning to the presented PA method. • How is the method understanding of designers with P/A CAD system experience? • How is the learning process of designers with P/A CAD system experience? Do they learn P/A methods faster than designers without PA/CAD experience? • Do designers with P/A CAD experience have their own design procedure and how do they use the new PA/CAD method? • How is the acceptance of designers with P/A CAD system experience related to the new method? • How is the method application of experienced and inexperienced designer with the PA design methods? How is the influence of P/A CAD knowledge to the PA design methods?

4. To which of these groups do you think that you are belonging?

☐Novice CAD-User ☐CAD-Advanced learner ☐CAD Expert ☐Non/Others:_______________________

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Categorization of the different kinds of CAD user during the implementation phase of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: To which of this group do you think that you are belonging?
Metric: Number of the users in the different categories. • How is the method understanding of designers in different categories? • How is the learning process of designers in different categories? • How is the acceptance of designers of designers in different categories? • How is the method application of designers in different categories?

5. What are your expectations in using PA CAD systems?

____

Goal:

Object: Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the expectation and imagination of the designer about PA system *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project
Question: What are your expectations in using PA CAD systems?
Metric: Identification of the factors which should be fulfilled by PA design systems. • Does the developed PA system fulfil the defined requirements by designers in real industrial context?

6. What is your definition and imagination of a design method?

____

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the expectation and imagination of the designer about PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project
Question: What is your definition and imagination of a design method?
Metric: Identification of the understanding of the designers related to the PA design method. • Does the developed PA method fulfil the defined requirements by designers in real industrial context?

7. To which of this group do you think that you are belonging?

☐Novice Method-User ☐Method-Advanced learner ☐Method Expert ☐Non/Others:______________________

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Categorization of the different kinds of method user during the implementation phase of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: To which of this group do you think that you are belonging?
Metric: Number of the users in the different categories. • How is the method understanding of designers in different categories? • How is the learning process of designers in different categories? • How is the acceptance of designers of designers in different categories? • How is the method application of designers in different categories?

8. Could you imagine that you work can be done easier by application of a PA CAD method?

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Categorization of the different kinds of method user during the implementation phase of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.

Question: Could you imagine that you work can be done easier by application of a PA CAD method?
Metric: Determination of the positive or negative feedback of the designers which are related to the questions about acceptance, understanding and learning to the presented PA method.

2) General question about the PA method

(Important general aspect of methods. Results of the literature survey)

2.1 Evaluation of the PA method representation:

9. Do you like to use the interface (the representation) of the developed PA method?

Don't like it **don't know** **I like it**

1	2	3	4	5

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method representation/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you like to use the interface (the representation) of the developed PA method?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method representation.

10. Do you think that the method steps and organisation of the presented PA method is clear and understandable?

Not clear **don't know** **clear**

1	2	3	4	5

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method representation/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that the method steps and organisation of the presented PA method is clear and understandable?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method representation.

11. Do you think that the presented PA method was pleasant to apply?

Difficult **don't know** **Pleasant**

1	2	3	4	5

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method representation/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.

Question: Do you think that the presented PA method was pleasant to apply?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method representation.

12. Do you think that the different steps of the presented PA method are continuous and interrelated?

disagree		don't know		fully agree
1	2	3	4	5

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method representation/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that the different steps of the presented PA method are continuous and interrelated?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method representation.

2.2 Evaluation of the PA method functionality:

13. Do you think that the functionality of the presented PA method fulfilled your expectations?

Don't fulfil		don't know		fulfil
1	2	3	4	5

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method functionality/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that the functionality of the presented PA method fulfilled your expectations?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method functionality.

2.3 Evaluation of the PA method learnability:

14. Do you think that you have learned the presented PA method quickly?

slow learning		don't know		quick learning
1	2	3	4	5

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method learning/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that you have learned the presented PA method quickly?

Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method learnability.

15. Do you think that you easily remember how to apply the presented PA method?

Difficult to remember **don't know** **Easy to remember**

1	**2**	**3**	**4**	**5**

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method learning/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that you easily remember how to apply the presented PA method?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method learnability.

16. Do you think that it was easy to use the presented PA method?

Difficult to use **don't know** **Easy to use**

1	**2**	**3**	**4**	**5**

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method learning/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that it was easy to use the presented PA method?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method learnability.

2.4 Evaluation of the PA method satisfaction

17. Do you think that you are satisfied with the presented PA method?

Frustrated **don't know** **Satisfied**

1	**2**	**3**	**4**	**5**

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method satisfaction/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that you are satisfied with the presented PA method?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method satisfaction.

18. Would you recommend the presented PA method to your colleagues?

wouldn't recommend **don't know** **would recommend**

1	**2**	**3**	**4**	**5**

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method satisfaction/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Would you recommend the presented PA method to my colleges?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method satisfaction.

19. Do you think that the presented PA method helps to design PA parts and assemblies in a better way?

Aggravation **don't know** **Improvement**

1	**2**	**3**	**4**	**5**

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method satisfaction/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that the presented PA method help to design PA parts and assemblies in a better way.
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method satisfaction.

20. Do you think that it is pleasant to apply the presented PA method?

Difficult **don't know** **Pleasant**

1	**2**	**3**	**4**	**5**

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method satisfaction/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that it is pleasant to apply the presented PA method?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method satisfaction.

2.4 Evaluation of the PA method Usefulness:

21. Do you think that the presented PA method helps to be more effective during the design process with PA CAD system?

Not efficient working **don't know** **efficient working**

1	**2**	**3**	**4**	**5**

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method Usefulness/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that the presented PA method helps to be more effective during the design process with PA CAD system?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method usefulness.

22. Do you think that the presented PA method helps to be more productive during the design process with PA CAD system?

Not productive working don't know productive working

1	2	3	4	5

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method Usefulness/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that the presented PA method helps to be more productive during the design process with PA CAD system?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method usefulness.

23. Do you think that the presented PA method gives more control over the design process with PA CAD systems?

Less control don't know more control

1	2	3	4	5

Goal: *Object:* Testing/Experiment phase of the PA design method *Purpose*: Evaluation of the PA method Usefulness/Usability of the PA method *Viewpoint:* Designer *Environment*: Evaluation of the Pilot project in real industrial context.
Question: Do you think that the presented PA method gives more control over the design process with PA CAD systems?
Metric: Number of positive or negative feedbacks of the designers which are related to the question about presented PA method usefulness.

24. What are the advantages and disadvantages of the presented PA design method from your point of view?

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Weakness of the method *Viewpoint:* Designer

Environment: Pilot project
Question: What are the advantages and disadvantages of the presented PA design method from your point of view? you think that you have time to apply the following method in your daily design work?
Metric: Quantification through the number of specified weaknesses of the method. This aspect help to identify the important aspects which should be improved.

3) Questions related to the single phases of the P/A design method (1. Specification phase → 2. Creation, modelling phase → 3. Modification phase)

3.1) Evaluation of the specification phase:

25. Did you understand the (Specification phase) of the P/A design method?

Difficult to understand don't know Easy to understand

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Mediation/Understanding, teaching, training of "Specification phase"/ *Viewpoint:* Designer *Environment*: Pilot project
Question: Did you understand the presented "specification phase" of the P/A design method?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with difficult there is a possibility to explain the reasons why this method step is i.e. difficult to understand. This aspect will help to identify potential improvements of this phase.

26. Does this method step (Specification phase) help for a better identification of the available parameter?

Poor representation don't know Better identification

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Identification of the relevant parameters/Research the influenced factors of this method step *Viewpoint:* Designer *Environment*: Pilot project
Question: Does this method step ("Specification phase") help for a better identification of the available parameter (geometrical and non geometrical design parameter)?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with poor there is a possibility to explain the reasons why this method step do not help to identify the relevant design parameters.

27. Does this method step (Specification phase) help for a better determination of the important parameter?

Aggravation (No changes) don't know Better determination

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Determination of the relevant parameters/Research the influenced factors *Viewpoint:* Designer *Environment*: Pilot project
Question: Does this method step ("Specification phase") help for a better identification of the available parameter (geometrical and non geometrical design parameter)?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why this method step do not help to determine the relevant design parameters. This aspect will help to identify improvements of this phase.

28. Does this method step help (Specification phase) for a better classification of available design parameter?

Aggravation (No changes) don't know Better classification

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Classification of the relevant parameters/Research the influenced factors *Viewpoint:* Designer *Environment*: Pilot project
Question: Does this method step help (Specification phase) for a better classification of the available design parameter (geometrical and non geometrical design parameter)?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why this method step do not help to classify the relevant design parameters.

29. Does this method step (Specification phase) help for a better representation of the relationship between the available design parameter?

Aggravation (No changes) don't know Better representation

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Representation of the relevant parameters/Research the influenced factors *Viewpoint:* Designer *Environment*: Pilot project
Question: Does this method step help (Specification phase) for a better representation of the available design parameter (geometrical and non geometrical design parameter)?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why this method step do not help to represent the relevant relationships between the design parameters.

30. Does the application of DSM in this method help for a better representation of the relationship between the available design parameters?

Aggravation (No changes) **don't know** **Better representation**

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Research of the application of DSM for representation of the relevant parameters *Viewpoint:* Designer *Environment*: Pilot project
Question: Does the application of DSM in this method help for a better representation of the relationship between the available design parameter?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why the application of DSM is not sufficient to represent the relationship between the relevant parameters.

31. Does this method step (Specification phase) help for a better identification of available associative relationships?

Aggravation (No changes) **don't know** **Better identification**

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Identification of the relevant associative relationships/Research the influenced factors *Viewpoint:* Designer *Environment*: Pilot project
Question: Does this method step (Specification phase) help for a better identification of the available associative relationships?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why this method step does not help to identify the relevant associative relationships.

32. Does this method step (Specification phase) help for a better determination of available associative relationships?

Aggravation (No changes) **don't know** **Better determination**

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Determination of the relevant associative relationships/Research the influenced factors *Viewpoint:* Designer *Environment*: Pilot project
Question: Does this method step (Specification phase) help for a better determination of available associative relationships?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why this method step does not help to

determine the relevant associative relationships between the geometrical entities.

33. Does this method step (Specification phase) help for a better classification of the available associative relationships?

Aggravation (No changes) don't know Better classification

1	2	3	4	5

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Classification of the relevant associative relationships/Research the influenced factors *Viewpoint:* Designer *Environment*: Pilot project
Question: Does this method step ("Specification phase") help for a better classification of the available associative relationships?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why this method step does not help to classify the relevant associative relationships between the geometrical entities.

34. Does the application of DSM in this method help for a better representation of the available associative relationships?

Aggravation (No changes) don't know Better representation

1	2	3	4	5

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Application of DSM for representation of the associative relationships *Viewpoint:* Designer *Environment*: Pilot project
Question: Does the application of DSM in this method help for a better representation of the available associative relationships?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why the application of DSM is not sufficient to represent the associative relationship between the geometrical entities.

35. Do you think that the presented method helps to design clearly structured CAD parts and assemblies?

Aggravation (No changes) don't know Better structuring

1	2	3	4	5

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Transparency/ Analyses the CAD parts/assembly structure/Research structural aspect. *Viewpoint:* Designer *Environment*: Pilot project
Question: Do you think that the presented method helps to design a clear structured CAD parts and

assemblies?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons why the structure is not complete.

36. Do you think that with the presented P/A design method relevant PA design information inputs and outputs are clearly structured?

Not clear structuring **don't know** **clear structuring**

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Transparency/structuring P/A design information input and output/Research structural aspect *Viewpoint:* Designer *Environment*: Pilot project
Question: Do you think that with the presented P/A design method relevant PA design information inputs and outputs are clear structured?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons in the important and relevant P/A design information inputs and outputs are considered.

3.2 Evaluation of the creation and modelling phase:

37. Do you think that the given (default) PAPS and PAAS help for a better creation of the P/A CAD part and assembly?

Aggravation **(No changes)** **don't know** **Better creation**

1	**2**	**3**	**4**	**5**

Why? ____

Goal: *Object:* Testing/Experiment phase of the method *Purpose*: Standardization of the P/A parts and assemblies/Research the standardization aspect *Viewpoint:* Designer *Environment*: Pilot project
Question: Do you think that the given (default) templates help for a better creation of the P/A CAD part and assembly?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain why the given templates are not sufficient structured

3.3 Evaluation of the modification phase:

38. Do you think that with the presented method created CAD PA components can be modified easier and faster?

Aggravation **(No changes)** **don't know** **faster modification**

1	**2**	**3**	**4**	**5**

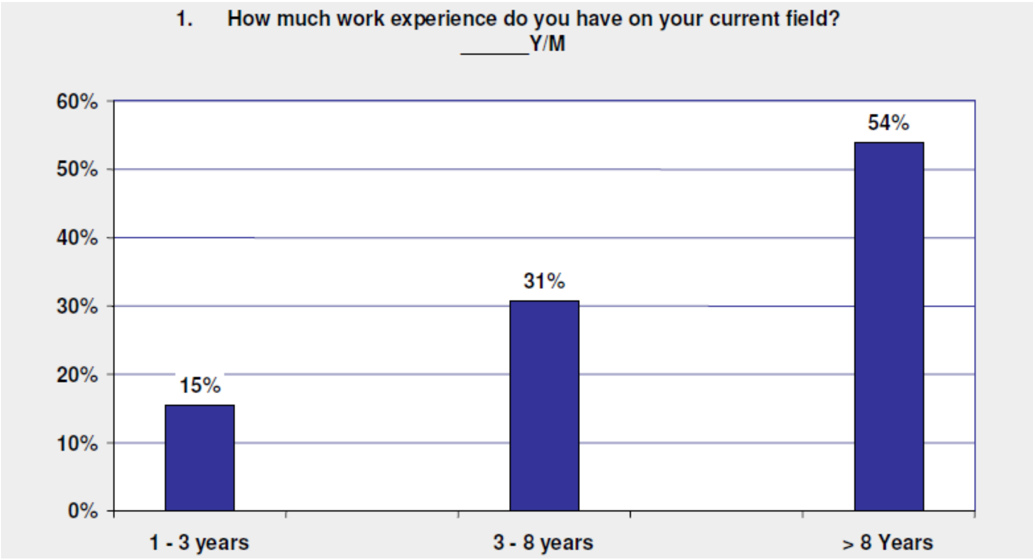
Why? ____

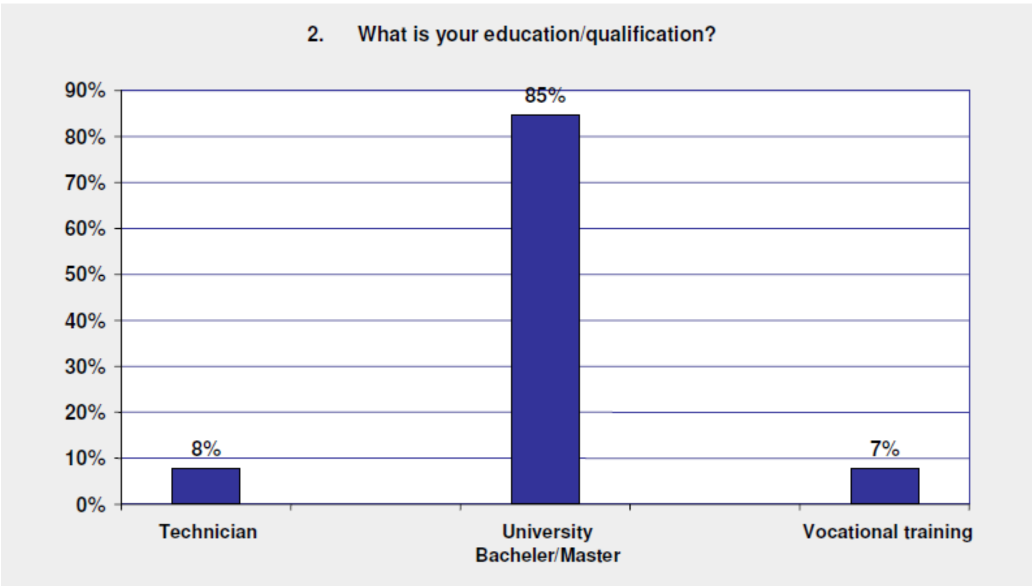
al: *ject:* Testing/Experiment phase of the method *rpose*: Usability of the P/A parts and assemblies/Research the standardization aspect

wpoint: Designer *vironment*: Pilot project
Question: Do you think that with the presented method the created CAD PA components can be modified easier?
Metric: Quantification through the number of positive and negative replies. In case of answering the question with No there is a possibility to explain the reasons if with the new method created parts and assemblies can be modified easier.

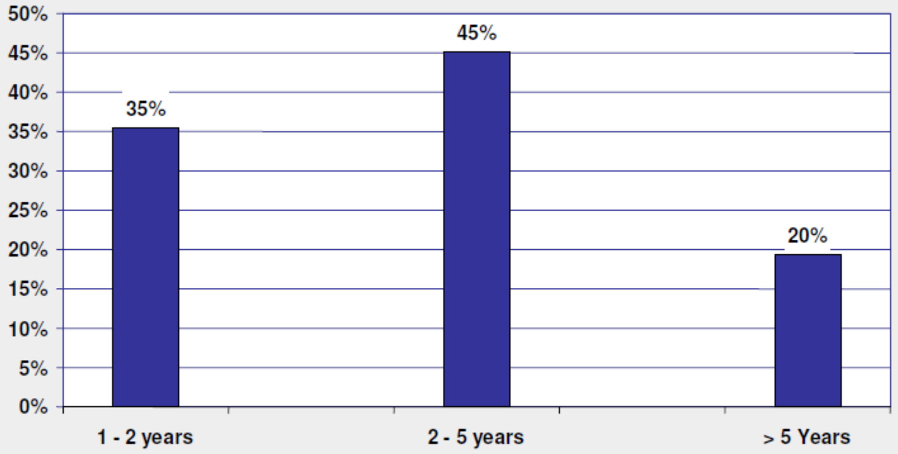
Appendix IV (Results of the qualitative evaluation)

This part of the appendix presents the results of the above mentioned (Appendix III) and defined questions. Furthermore it shows how the designers responded to the questions related to their background and to the PARAMASS approach.

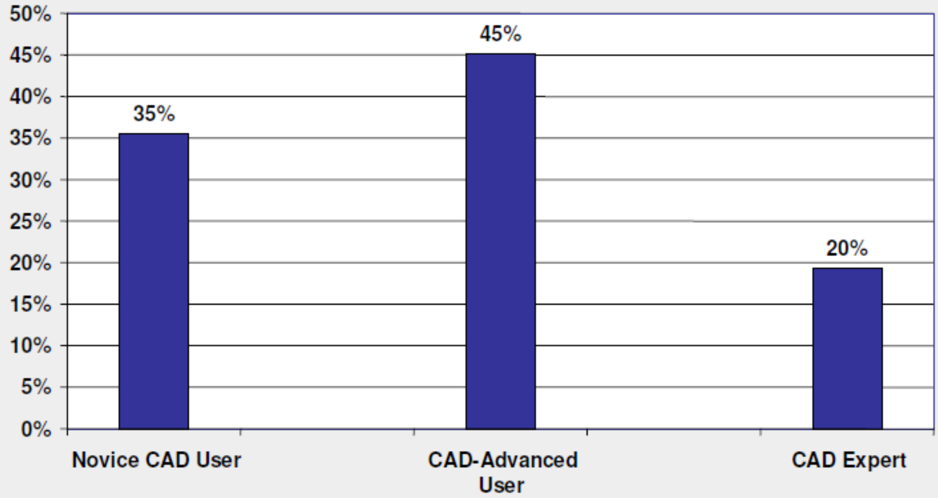




3. How much work experience do you have with parametric associative CAD systems? __________Years/Month



4. To which of this group do you think that you are belonging?



5. What are your expectations in using parametric associative CAD systems?

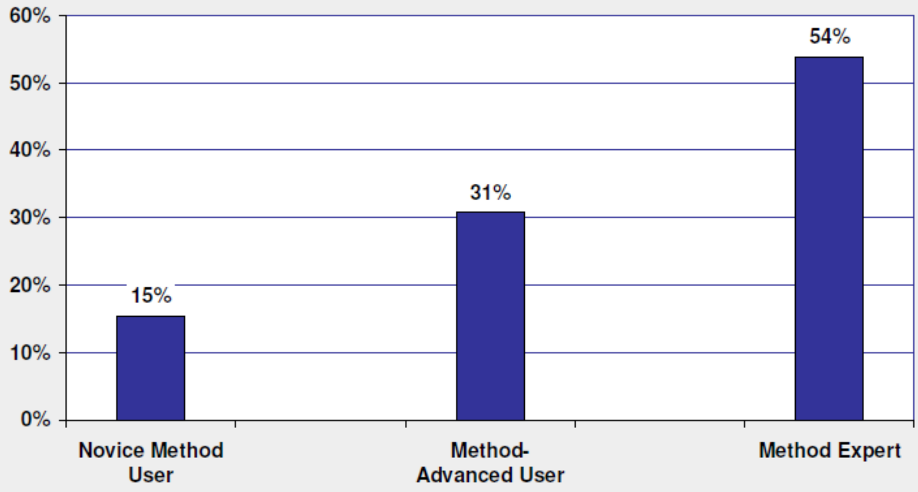
1. The content of the created parametric associative parts and assemblies should be easy to understand (with less effort)
2. Safe/secure creation of associative relationships between components and parameters
3. Simple change of the parametric associative parts and assemblies
4. Ability to create clear structured parts and assemblies
5. Creation of transparent parts and assemblies → Representation of the relationships between parameters and associative relationships

6. What is your imagination of a design method?

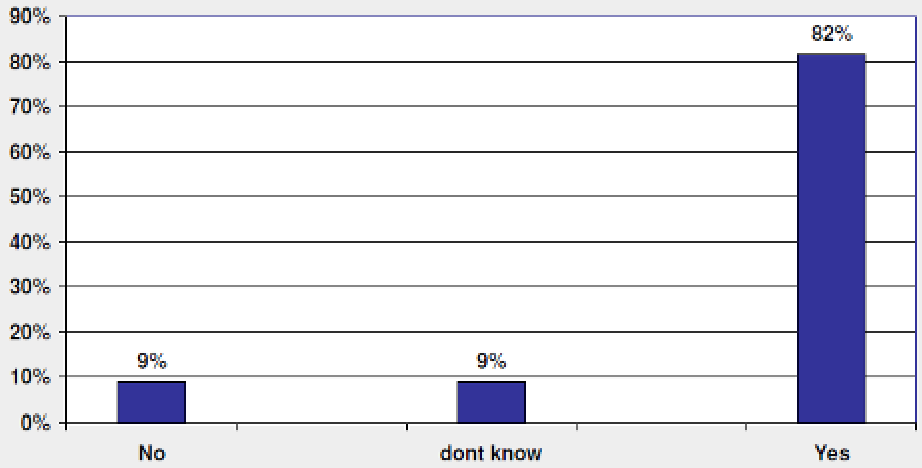
A Method should be:

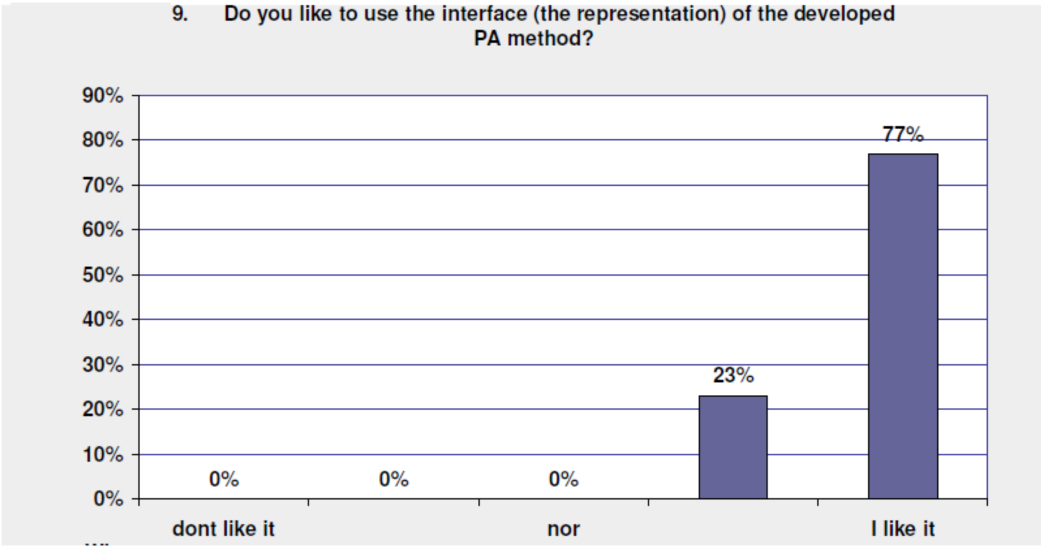
- Applicable and work in real design environment.
- Simple and self-explanatory.
- Structured logically.
- Able to model and change PA components faster and easier (also parts and assemblies which are created by suppliers and other designers).
- Able to create simple and well structured parametric associative parts and assemblies.
- Able to create a "common modeling language" between the designers.
- Able to create transparent parts and assemblies → Identification, determination and representation of the relationships between parameters and associative relationships

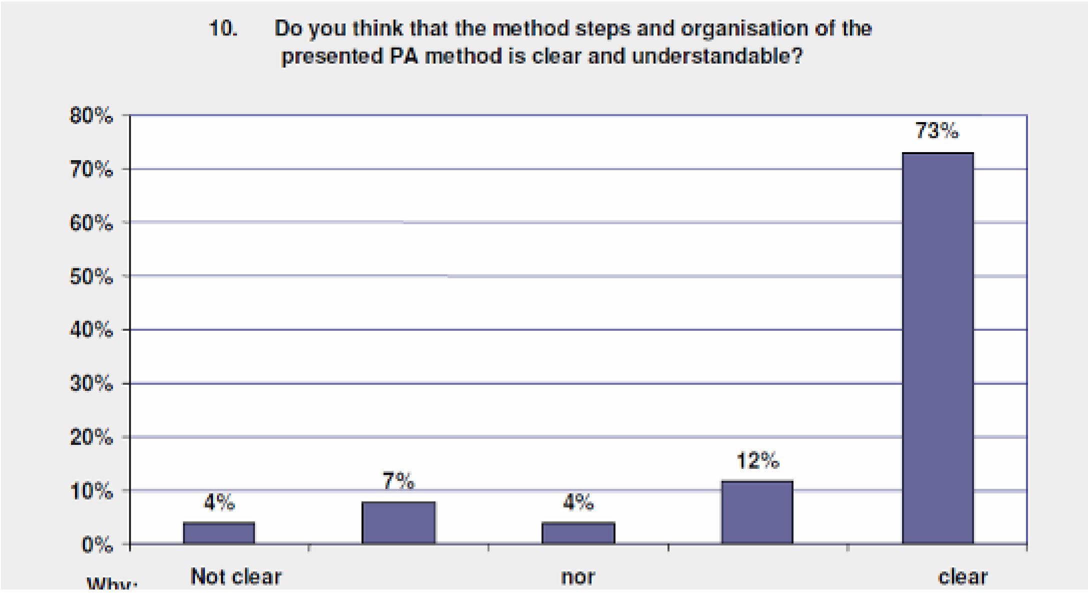
7. To which of this group do you think that you are belonging?

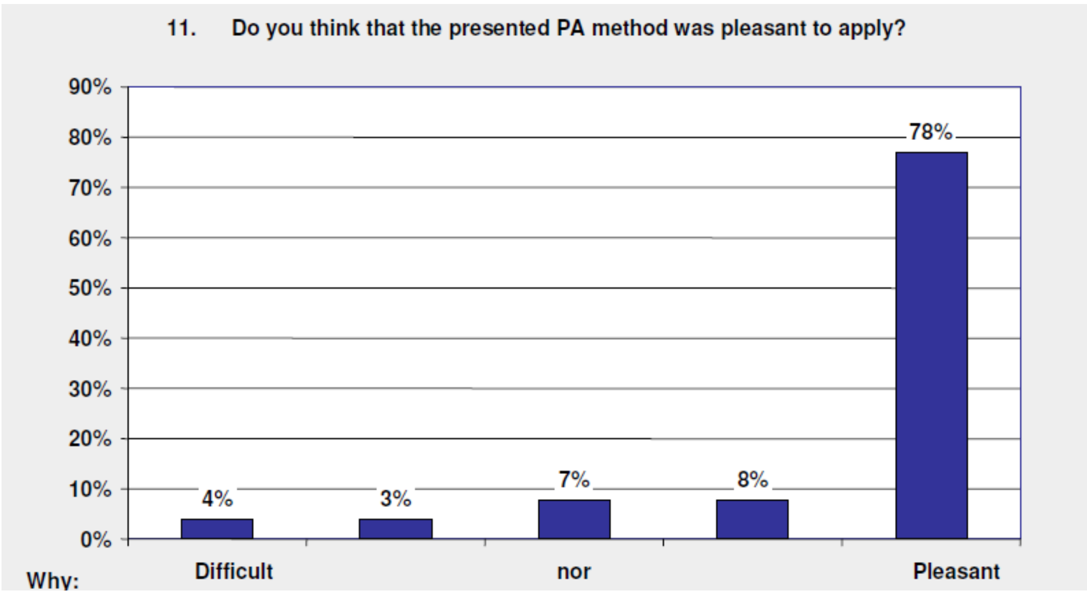


8. Could you imagine that you work can be done easier by application of a parametric associative CAD method?

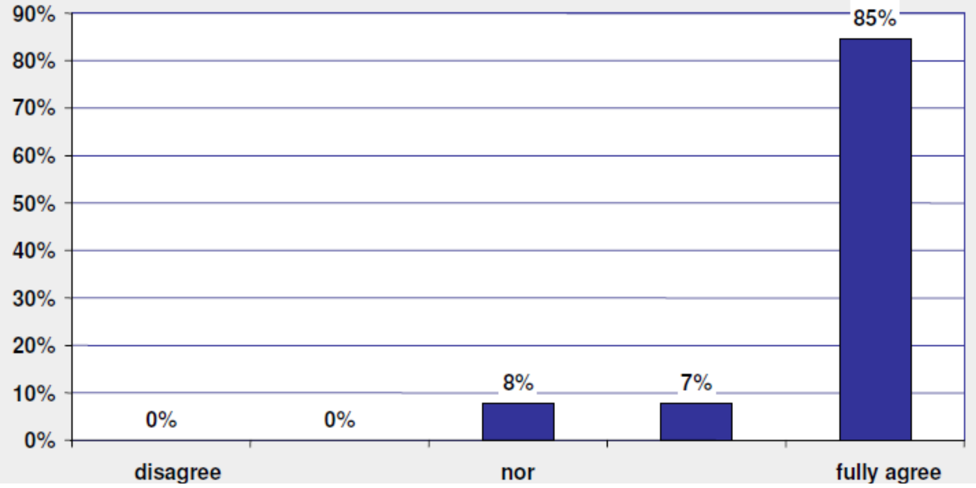



9. Do you like to use the interface (the representation) of the developed PA method?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
0%
0%
23%
77%
dont like it
nor
I like it

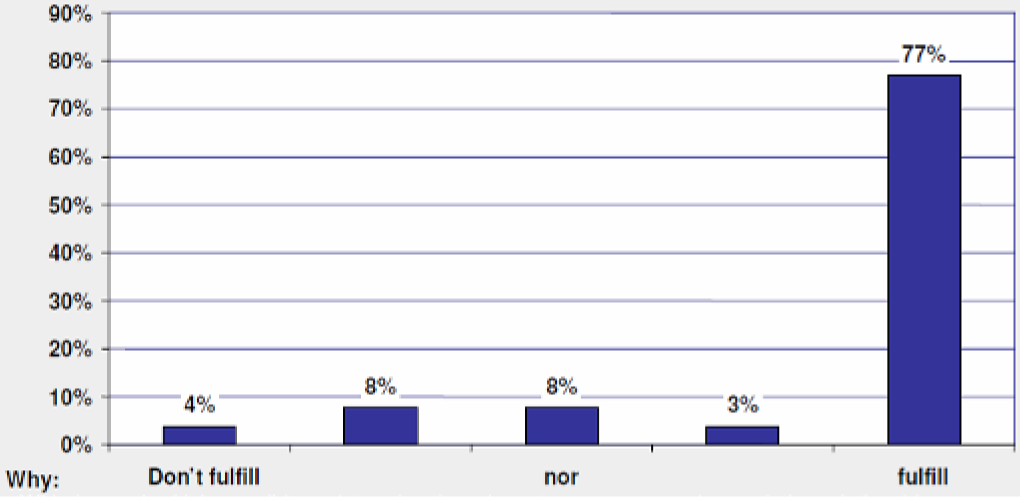

10. Do you think that the method steps and organisation of the presented PA method is clear and understandable?
80%
70%
60%
50%
40%
30%
20%
10%
0%
4%
7%
4%
12%
73%
Not clear
nor
clear


11. Do you think that the presented PA method was pleasant to apply?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
4%
3%
7%
8%
78%
Why:
Difficult
nor
Pleasant

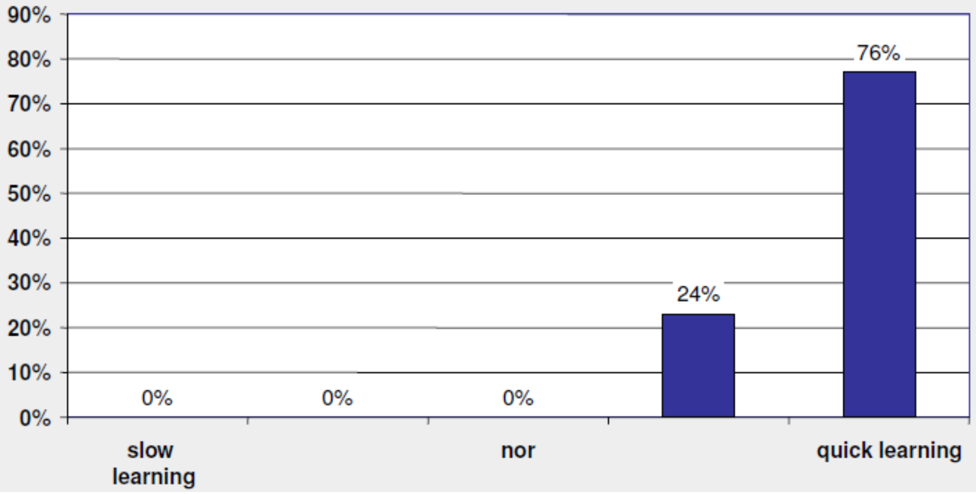
12. Do you think that the different steps of the presented PA method are continuous and interrelated?



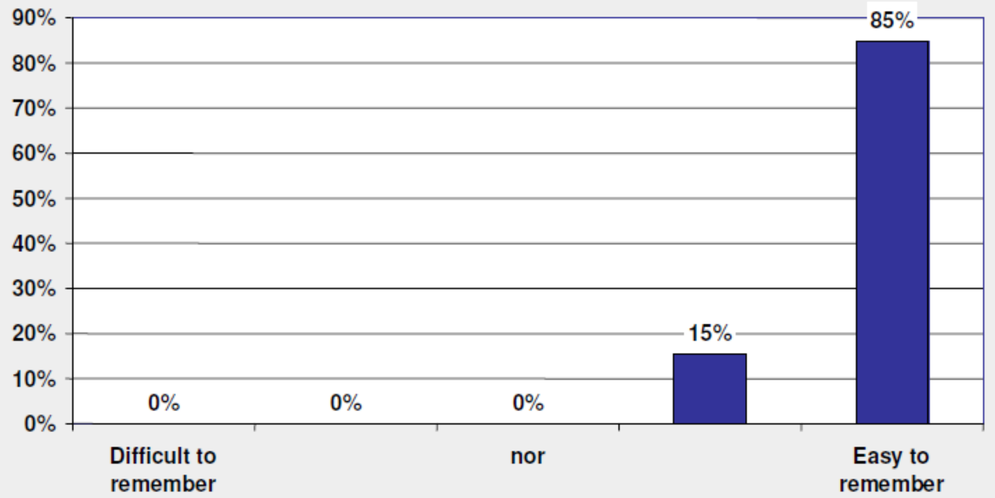
13. Do you think that the functionality of the presented PA method fulfilled your expectations?



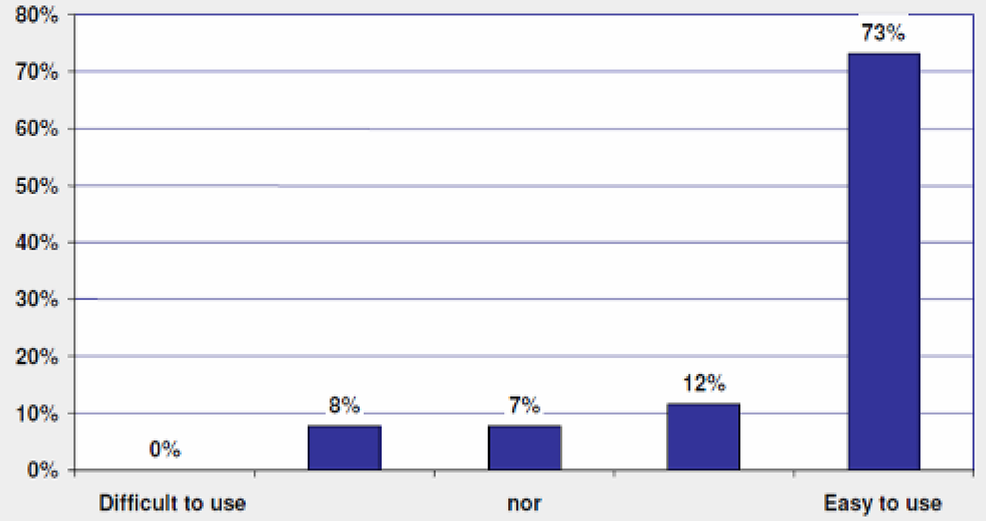
14. Do you think that you have learned the presented PA method quickly?



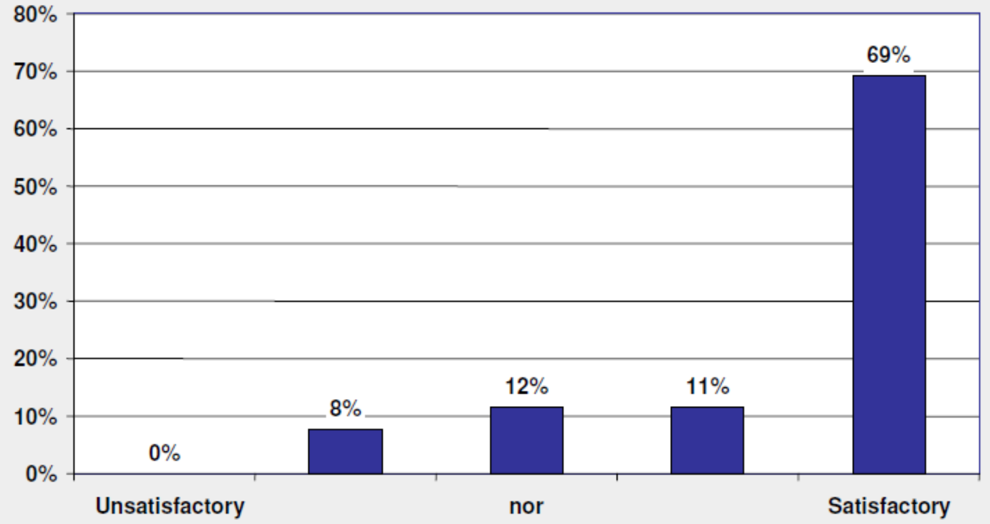
15. Do you think that you easily remember how to apply the presented PA method?

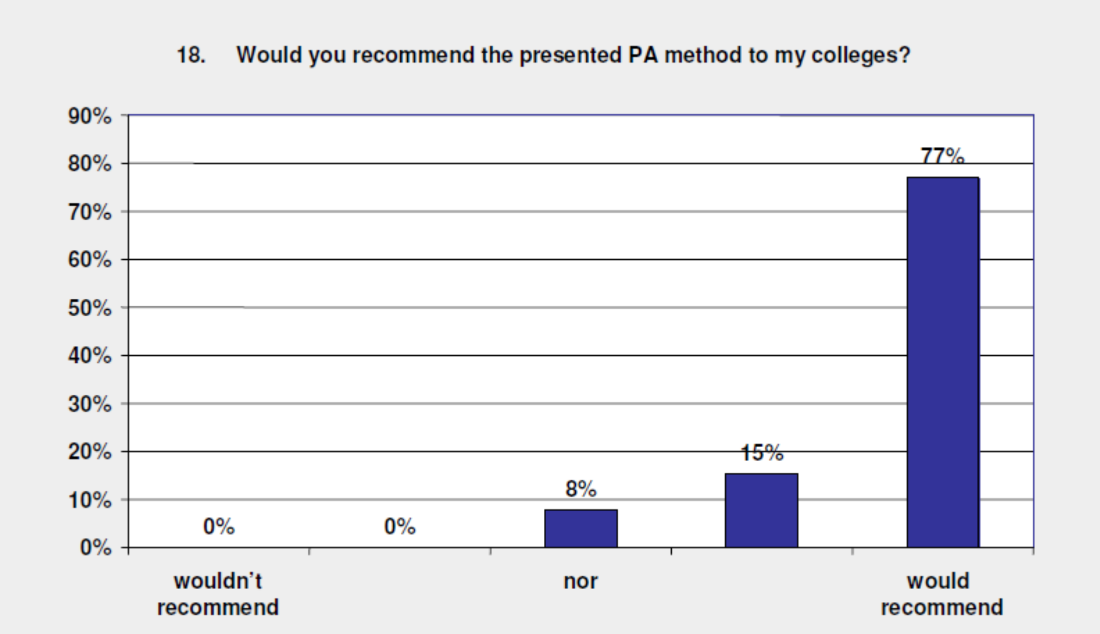


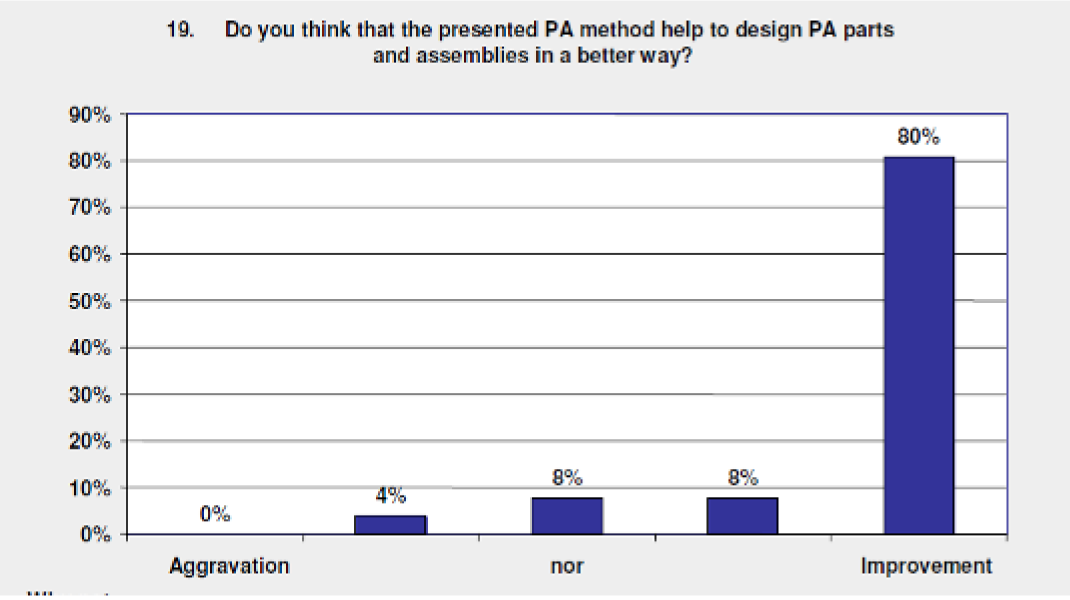
16. Do you think that it was easy to use the presented PA method?

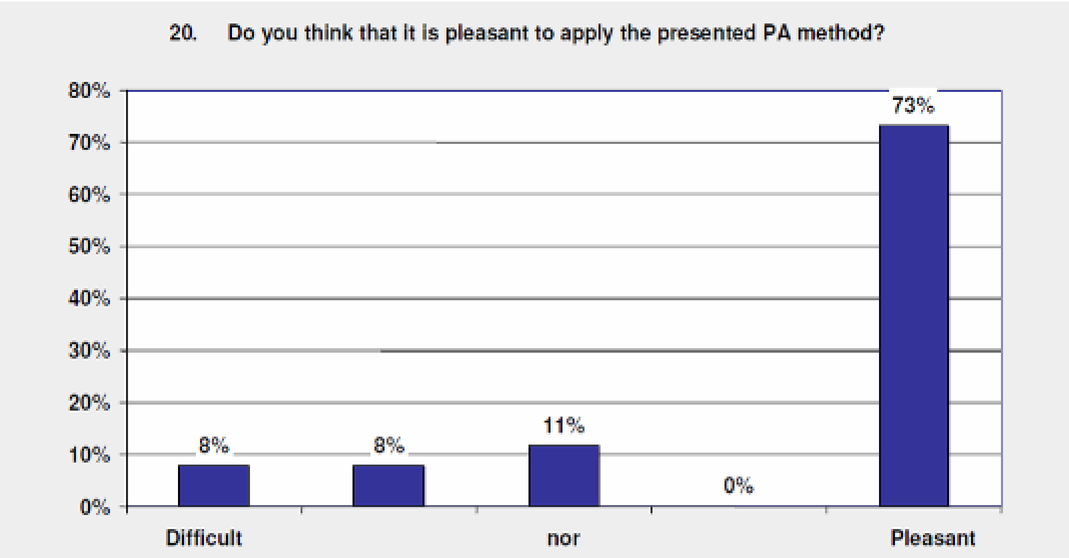


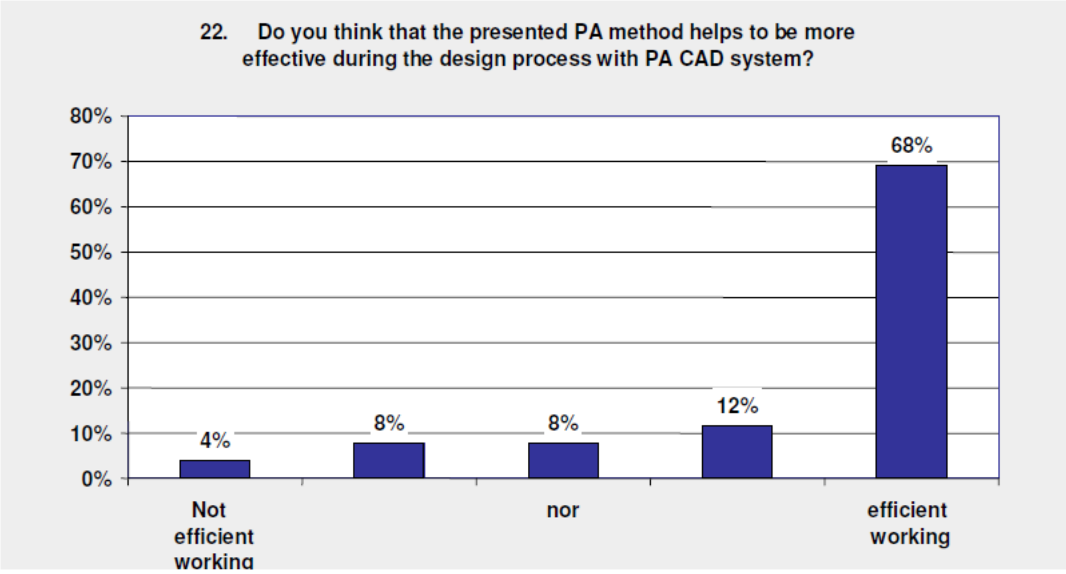
17. Do you think that you are satisfied with the presented PA method?

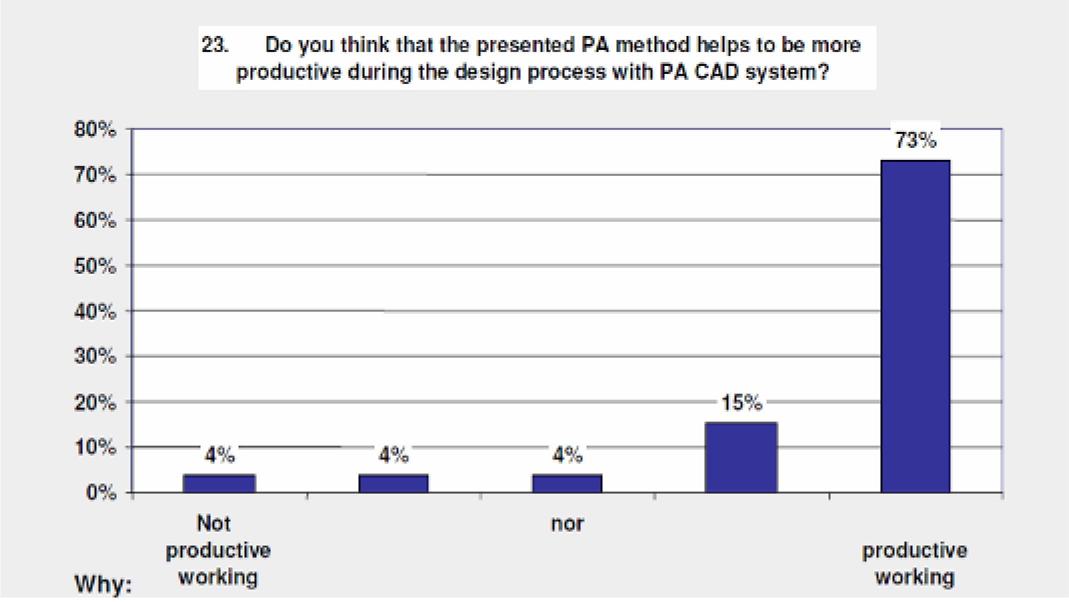


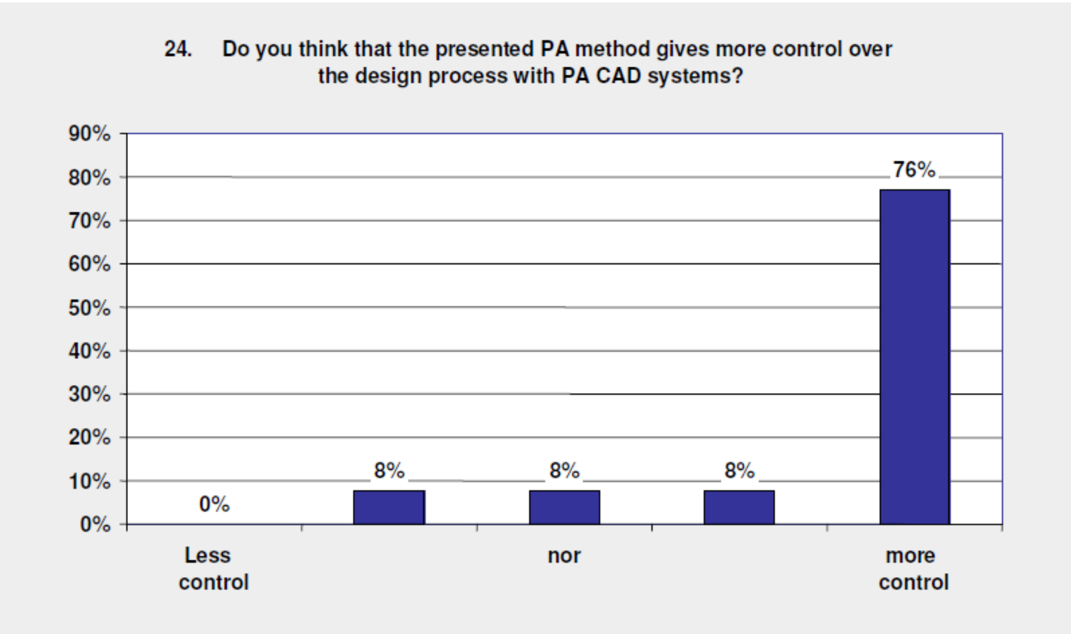

18. Would you recommend the presented PA method to my colleges?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
0%
8%
15%
77%
wouldn't recommend
nor
would recommend


19. Do you think that the presented PA method help to design PA parts and assemblies in a better way?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
4%
8%
8%
80%
Aggravation
nor
Improvement

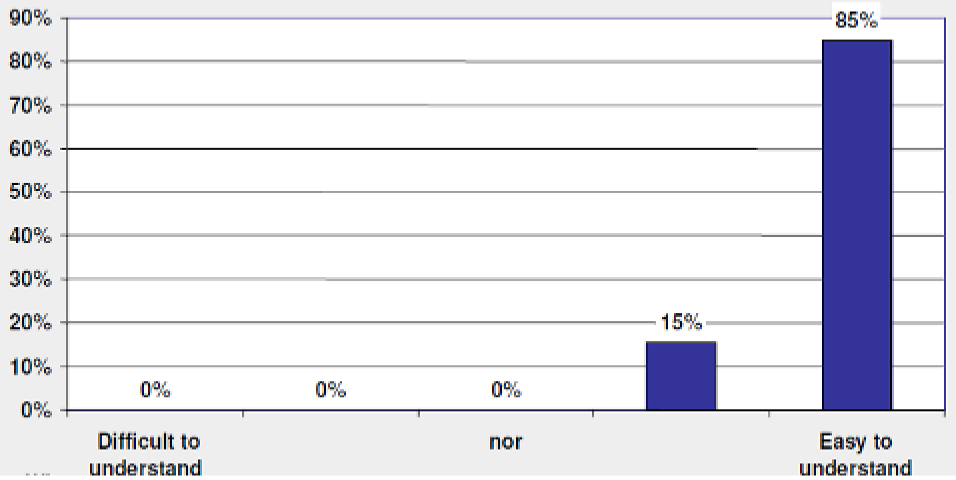

20. Do you think that it is pleasant to apply the presented PA method?
80%
70%
60%
50%
40%
30%
20%
10%
0%
8%
8%
11%
0%
73%
Difficult
nor
Pleasant


22. Do you think that the presented PA method helps to be more effective during the design process with PA CAD system?
80%
70%
60%
50%
40%
30%
20%
10%
0%
4%
8%
8%
12%
68%
Not efficient working
nor
efficient working

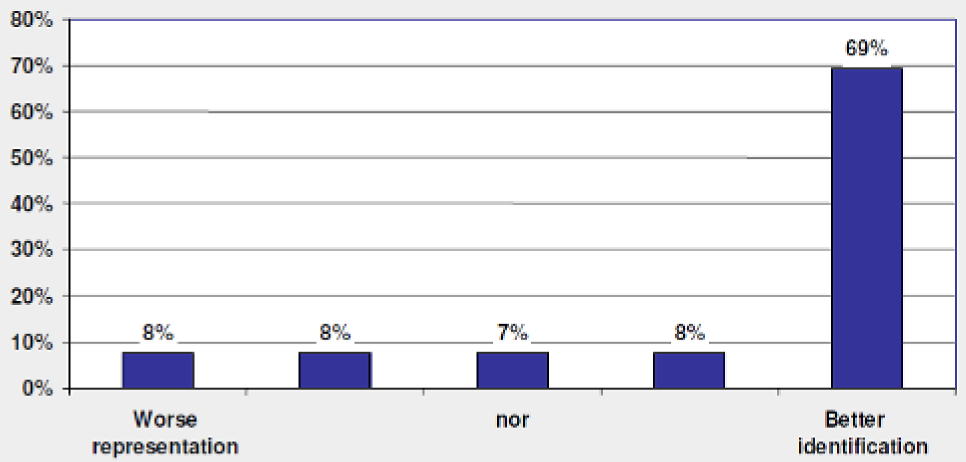

23. Do you think that the presented PA method helps to be more productive during the design process with PA CAD system?
80%
70%
60%
50%
40%
30%
20%
10%
0%
4%
4%
4%
15%
73%
Not productive working
nor
productive working
Why:


24. Do you think that the presented PA method gives more control over the design process with PA CAD systems?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
8%
8%
8%
76%
Less control
nor
more control

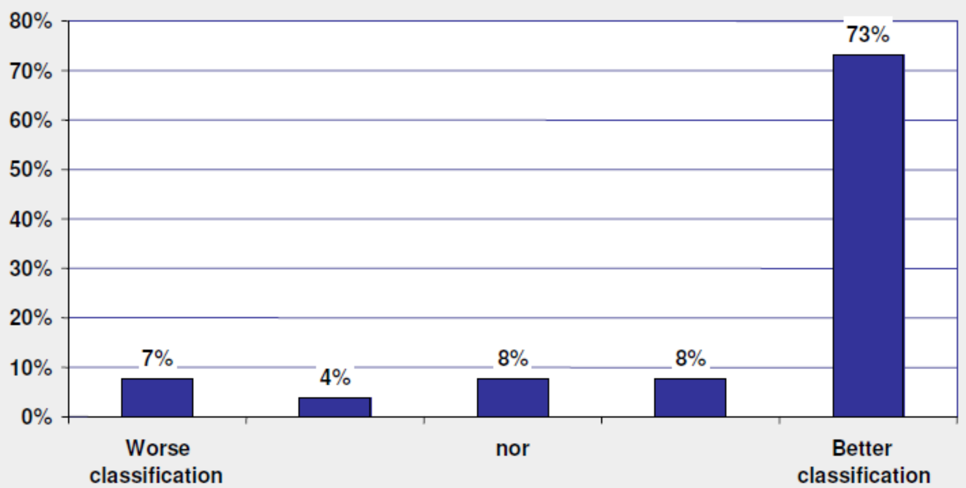
26. Did you understand the (Specification phase) of the P/A design method?

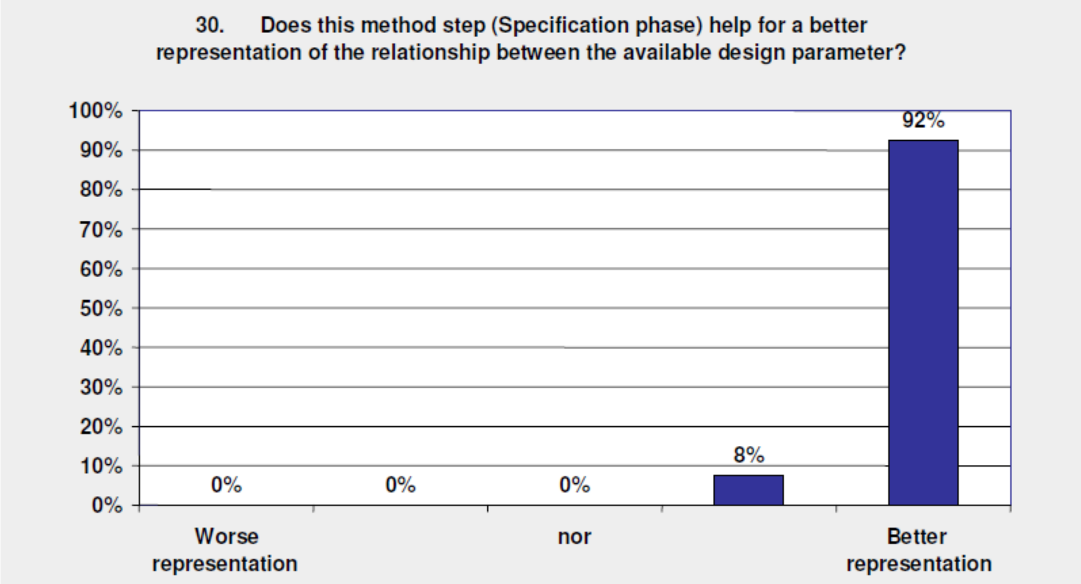


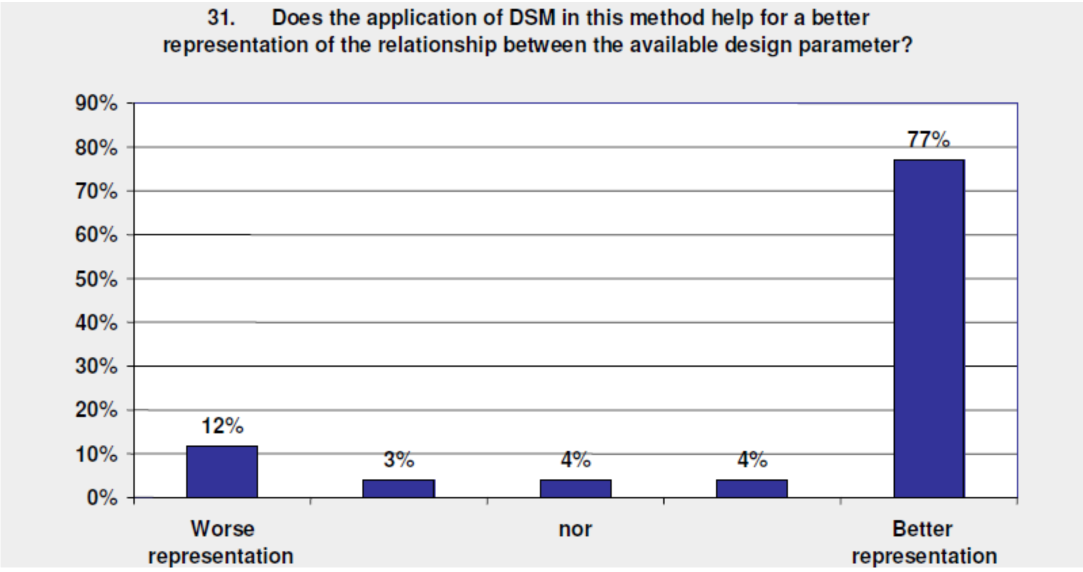
27. Does this method step (Specification phase) help for a better identification of the available parameter?

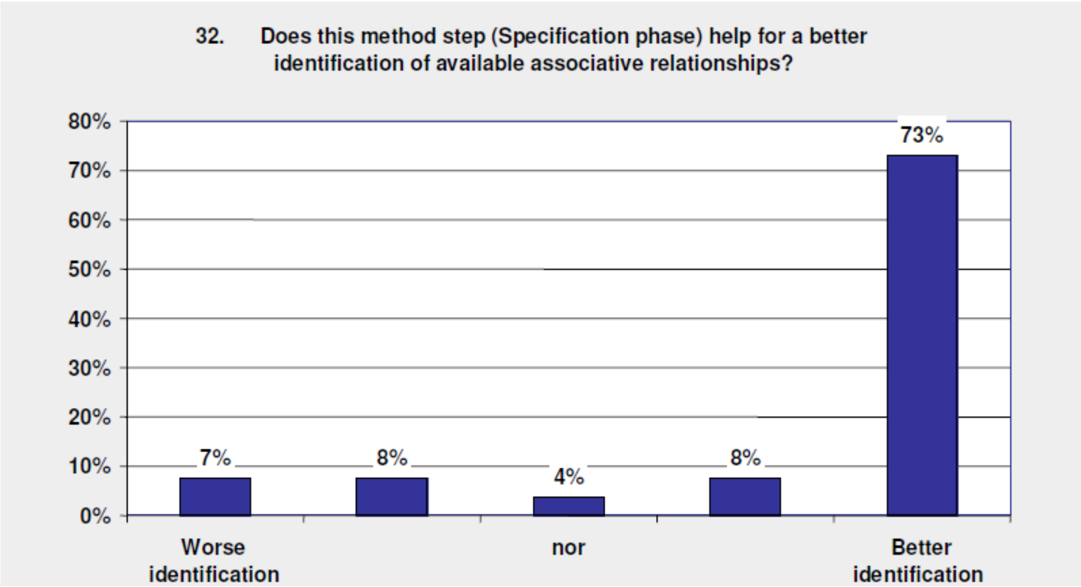


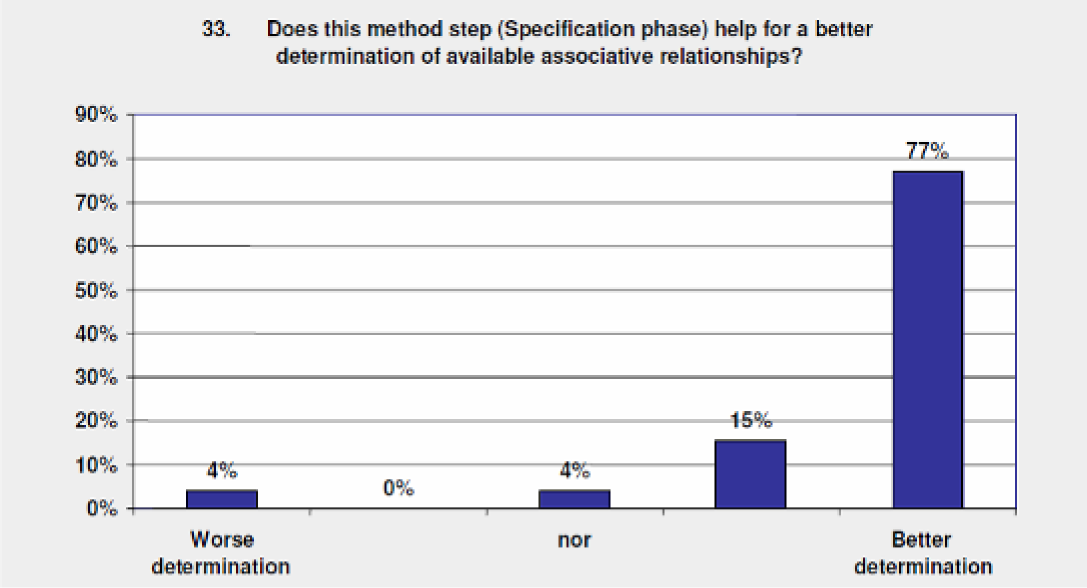
29. Does this method step help (Specification phase) for a better classification of available design parameter?

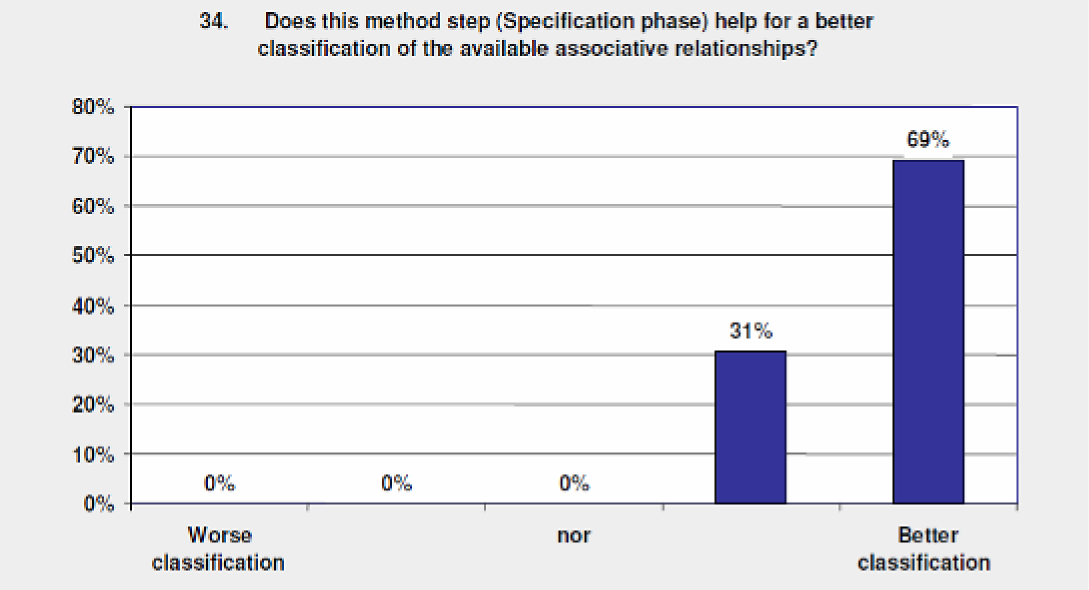


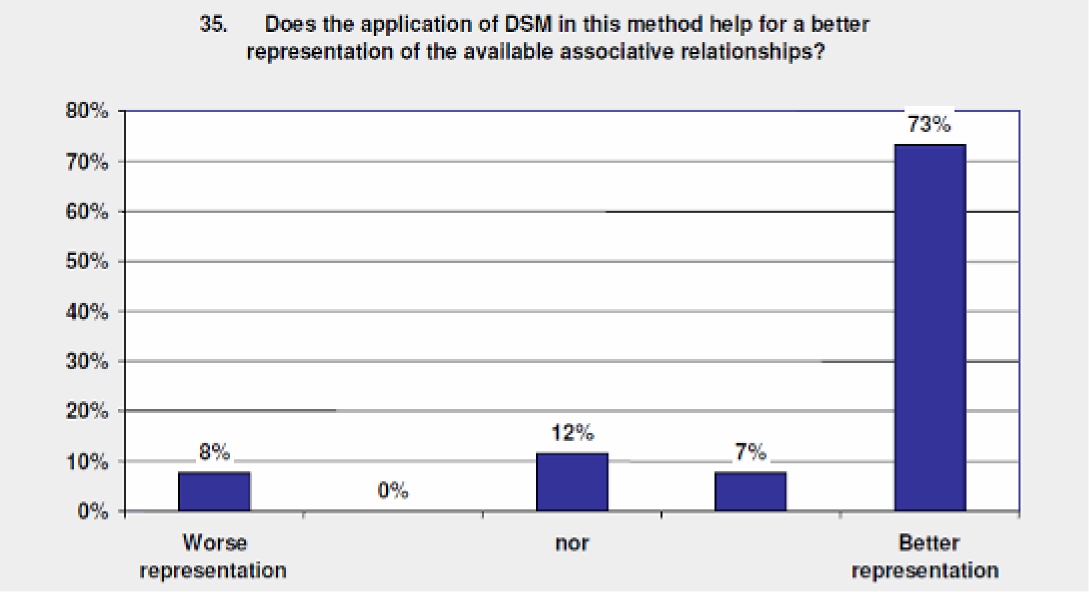

30. Does this method step (Specification phase) help for a better representation of the relationship between the available design parameter?
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
0%
0%
8%
92%
Worse representation
nor
Better representation

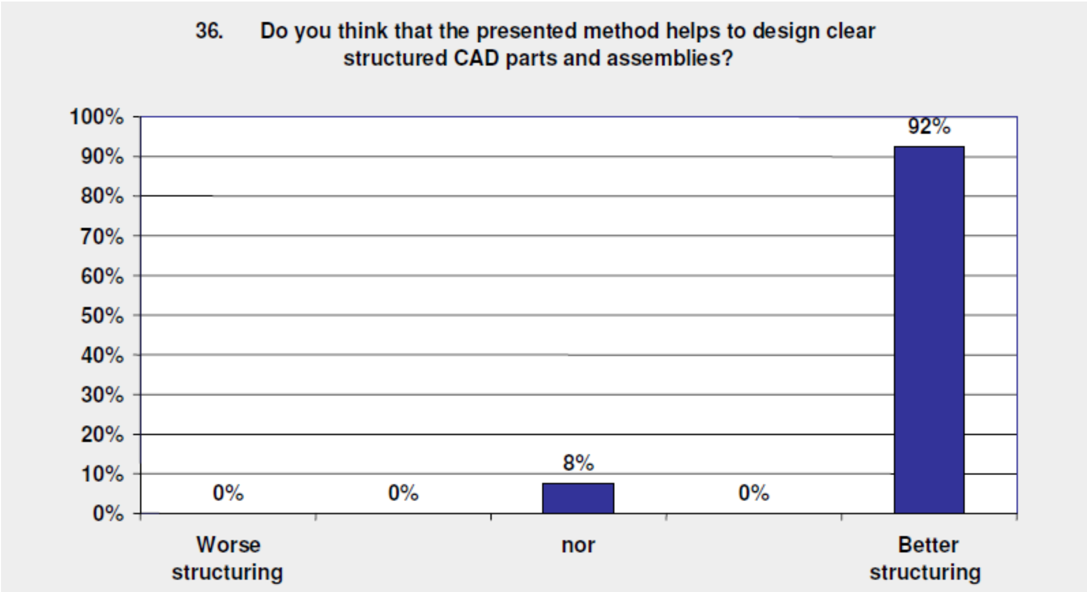

31. Does the application of DSM in this method help for a better representation of the relationship between the available design parameter?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
12%
3%
4%
4%
77%
Worse representation
nor
Better representation

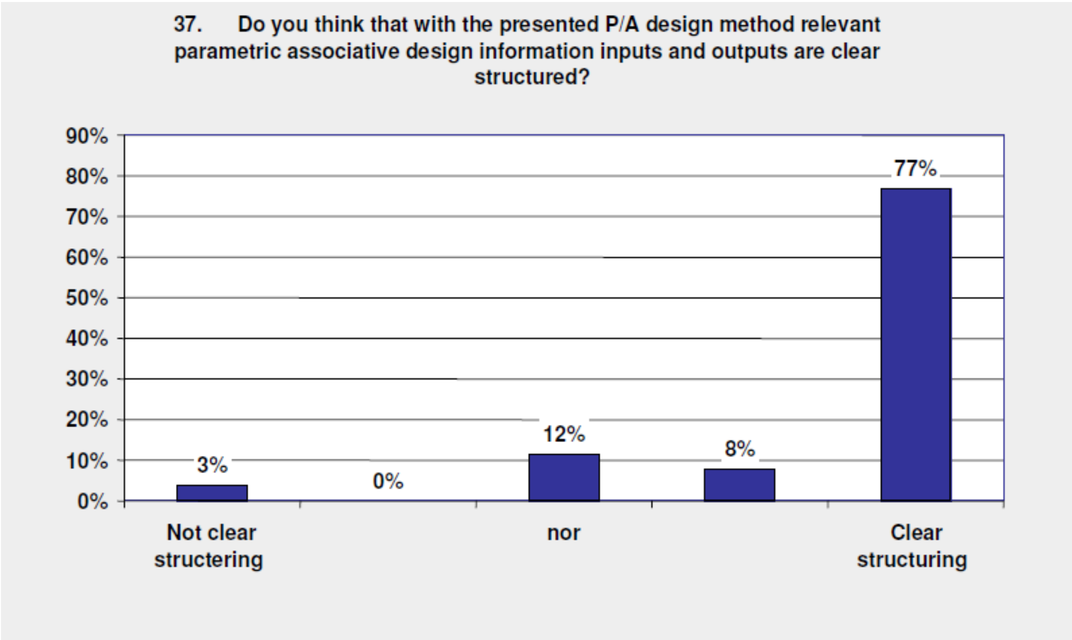

32. Does this method step (Specification phase) help for a better identification of available associative relationships?
80%
70%
60%
50%
40%
30%
20%
10%
0%
7%
8%
4%
8%
73%
Worse identification
nor
Better identification

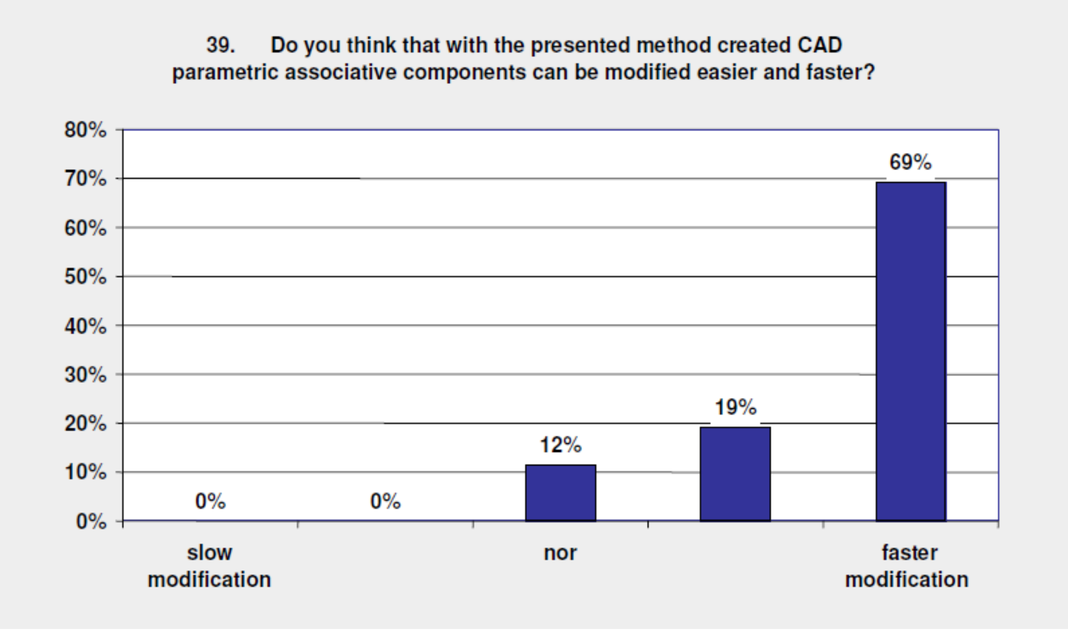

33. Does this method step (Specification phase) help for a better determination of available associative relationships?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
4%
0%
4%
15%
77%
Worse determination
nor
Better determination


34. Does this method step (Specification phase) help for a better classification of the available associative relationships?
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
0%
0%
31%
69%
Worse classification
nor
Better classification


35. Does the application of DSM in this method help for a better representation of the available associative relationships?
80%
70%
60%
50%
40%
30%
20%
10%
0%
8%
0%
12%
7%
73%
Worse representation
nor
Better representation


36. Do you think that the presented method helps to design clear structured CAD parts and assemblies?
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
0%
8%
0%
92%
Worse structuring
nor
Better structuring


37. Do you think that with the presented P/A design method relevant parametric associative design information inputs and outputs are clear structured?
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
3%
0%
12%
8%
77%
Not clear structering
nor
Clear structuring


39. Do you think that with the presented method created CAD parametric associative components can be modified easier and faster?
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
0%
12%
19%
69%
slow modification
nor
faster modification

Appendix V (Definition of the Use Cases and the results)

This part of the thesis presents the defined Use Cases related to the PARAMASS approach. It shows the different framework of the Use Cases for each phase of the PARAMASS approach. These Use Cases have been tested during the quantitative evaluation of the approach in a number of different workshops in which the researcher was able to accompany the designers. In the end 120 Use Cases were defined and tested by 10 different groups of designers (6 designers in each group). The evaluation process was done in an automotive company over a six-month period in 2011. In this section the Use Cases for a piston, connection rod, oil pan and cylinder head will be shown.

1) Use Case framework for a piston:

Method Evaluation System (MESY)

Framework of the use case:

USE CASE NAME: Identification and determination of the piston parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Identification and determination of the piston parameters
Goal of the use case:	Identification and determination of certain parameters
Workflow of the use case:	1. Open the piston in CATIA V5 (CAD data name: piston.part). 2. Identify the following parameters: • ***Geometry parameters***: piston diameter, piston length, compression height, piston bore, top land, compression ring grove, piston radius • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:*** position of the piston bore, tolerance of the piston bore etc. 3. Close the piston in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the piston part in CATIA V5.
Explanatory notes	The time during the identification of the different parameters will be captured and measured.

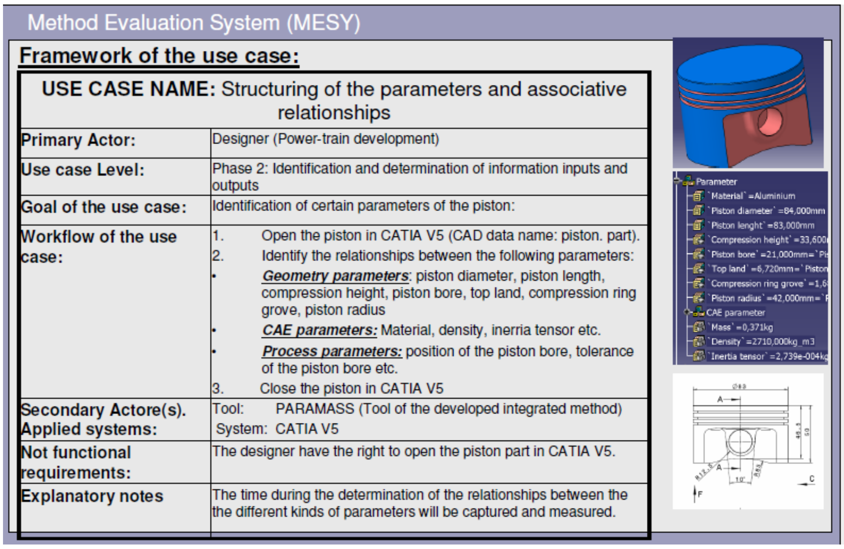
PHASE 1

Method Evaluation System (MESY)

Framework of the use case:

USE CASE NAME: Representation of the relationships between the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Representation of the relationships between the parameters and associative relationships
Goal of the use case:	Identification of certain parameters of the piston:
Workflow of the use case:	1. Open the piston in CATIA V5 (CAD data name: piston.part). 2. Identify the relationships between the following parameters: • ***Geometry parameters***: piston diameter, piston length, compression height, piston bore, top land, compression ring grove, piston radius 3. Close the piston in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the piston part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

PHASE 1

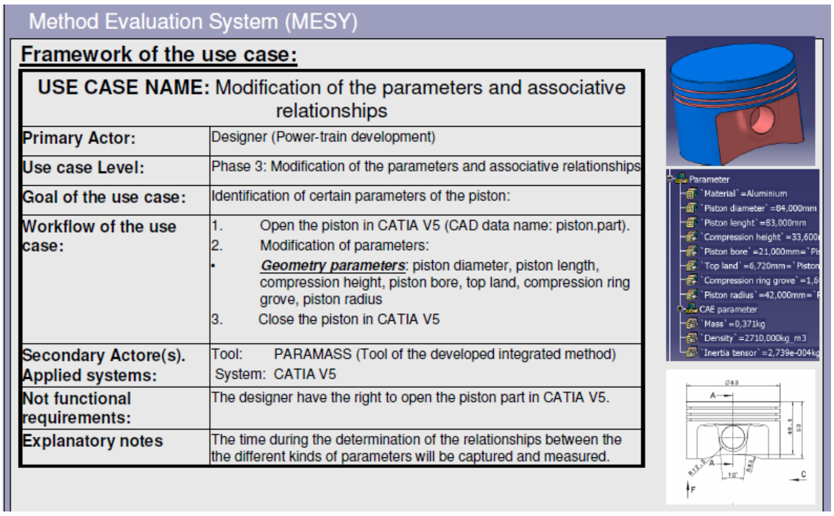


Method Evaluation System (MESY)

Framework of the use case:

USE CASE NAME: Structuring of the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 2: Identification and determination of information inputs and outputs
Goal of the use case:	Identification of certain parameters of the piston:
Workflow of the use case:	1. Open the piston in CATIA V5 (CAD data name: piston. part). 2. Identify the relationships between the following parameters: • ***Geometry parameters***: piston diameter, piston length, compression height, piston bore, top land, compression ring grove, piston radius • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:*** position of the piston bore, tolerance of the piston bore etc. 3. Close the piston in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the piston part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

PHASE 2

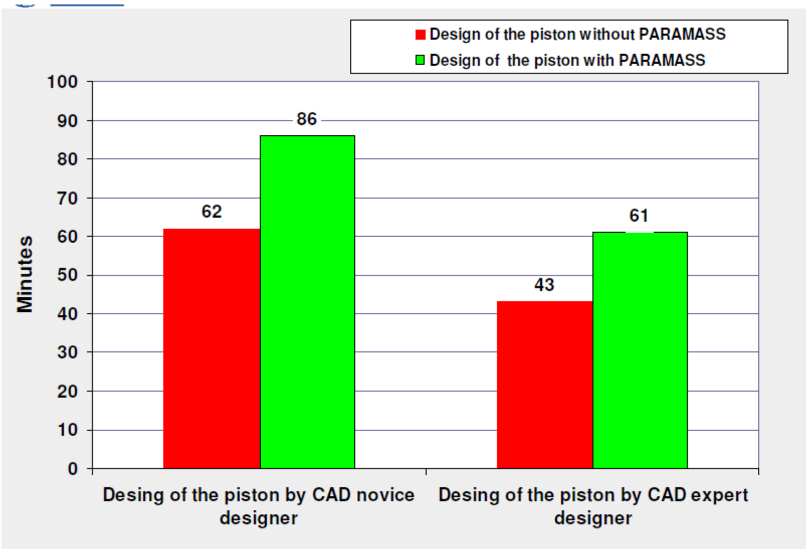


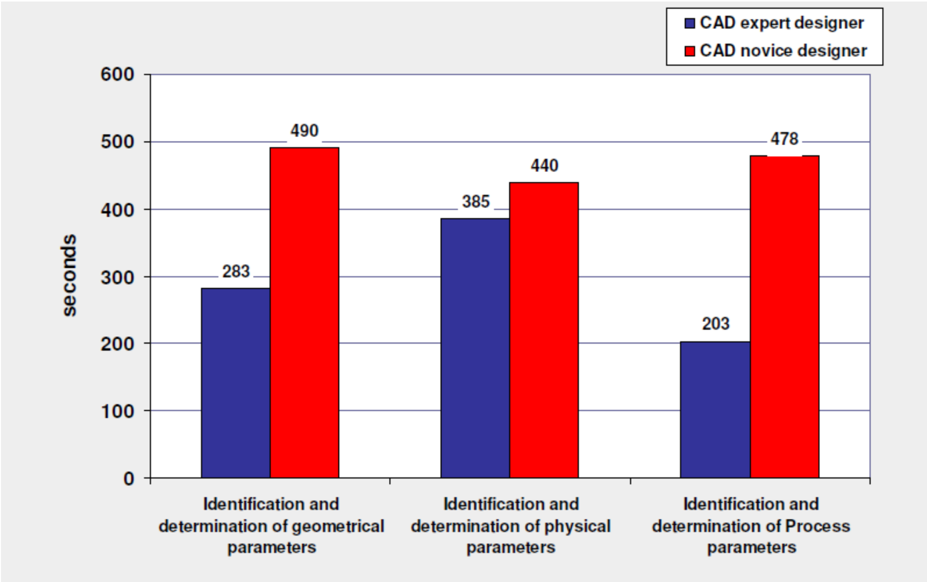
Method Evaluation System (MESY)

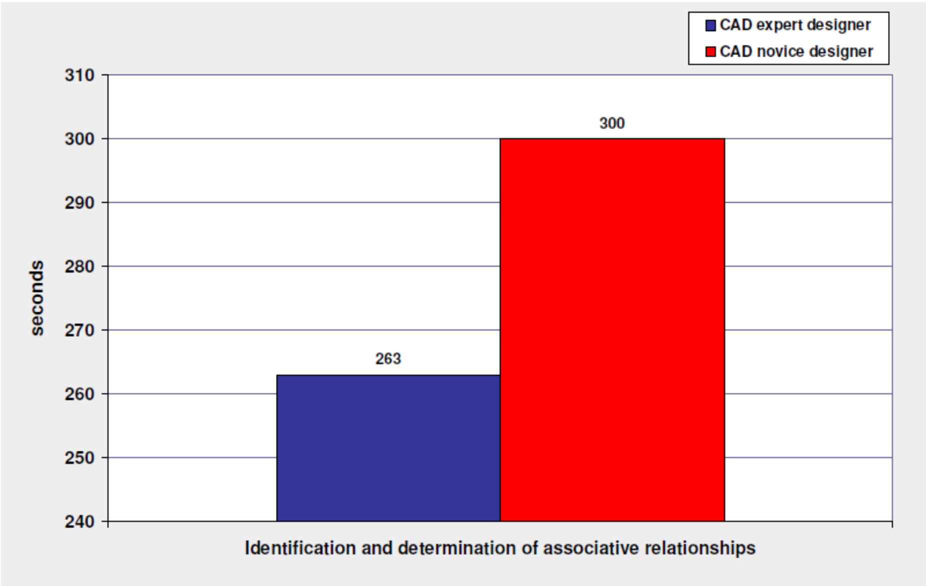
Framework of the use case:

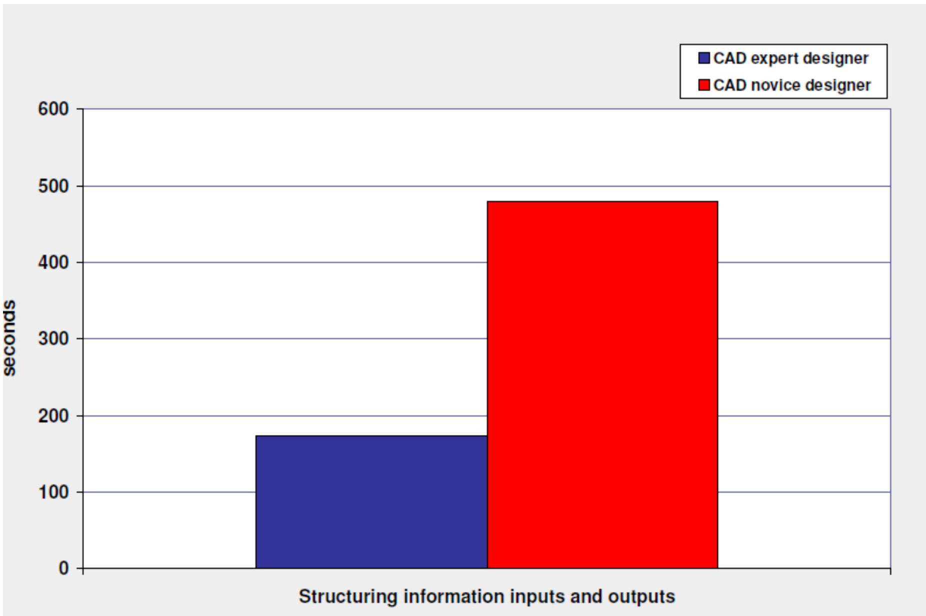
USE CASE NAME: Modification of the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 3: Modification of the parameters and associative relationships
Goal of the use case:	Identification of certain parameters of the piston:
Workflow of the use case:	1. Open the piston in CATIA V5 (CAD data name: piston.part). 2. Modification of parameters: • ***Geometry parameters***: piston diameter, piston length, compression height, piston bore, top land, compression ring grove, piston radius 3. Close the piston in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the piston part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

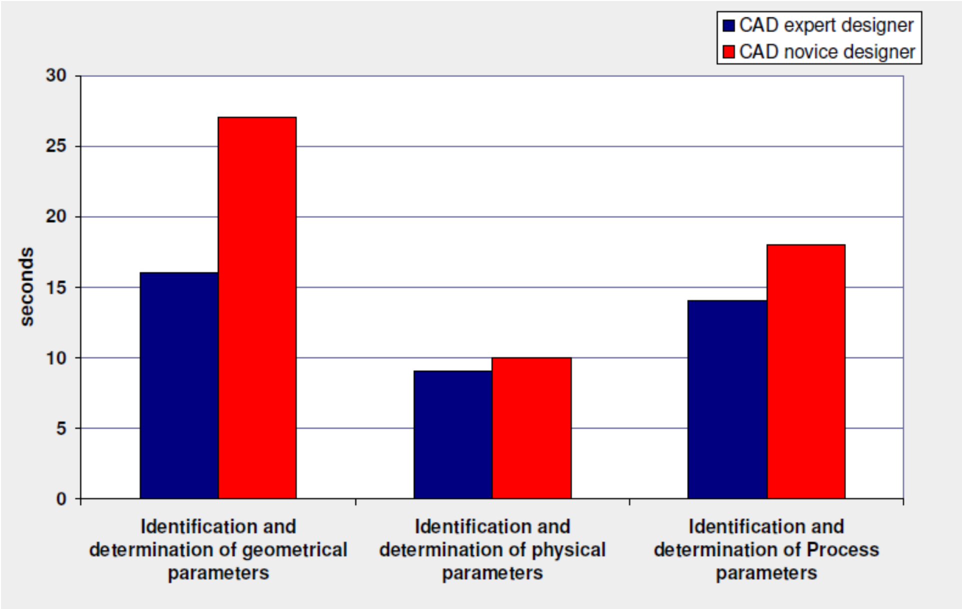
PHASE 3Use Case results for the piston:

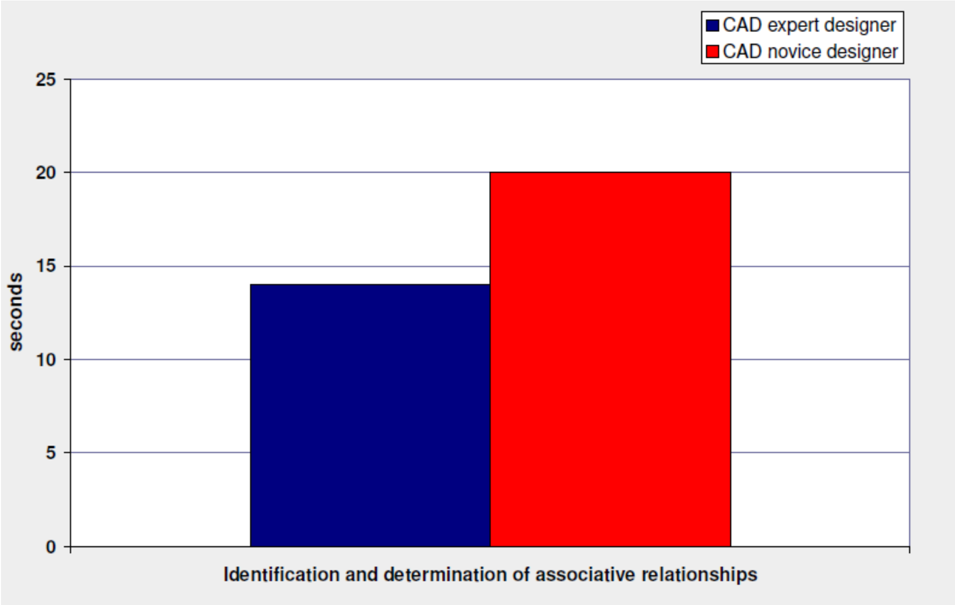


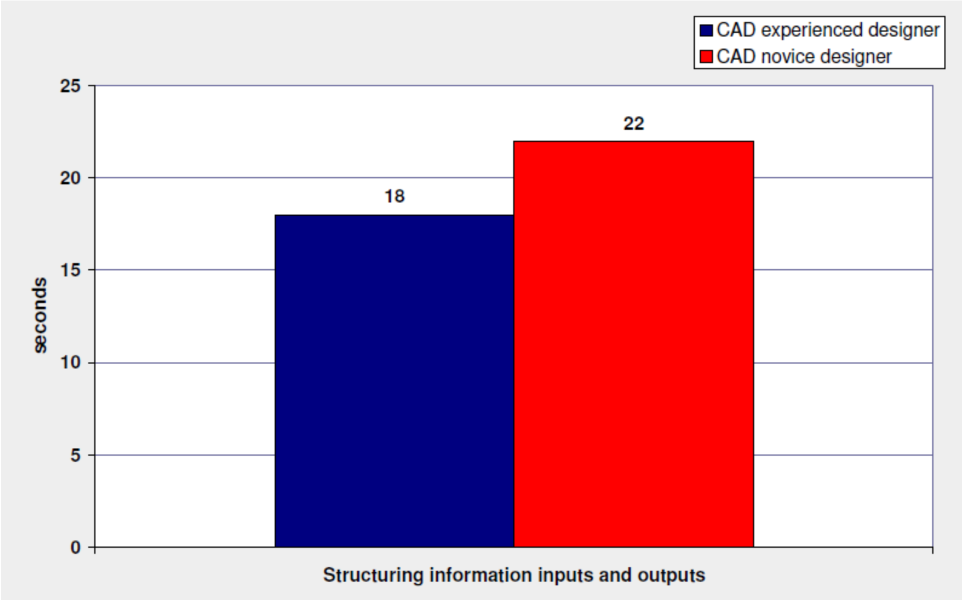

CAD expert designer
CAD novice designer
seconds
600
500
400
300
200
100
0
490
440
478
283
385
203
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters

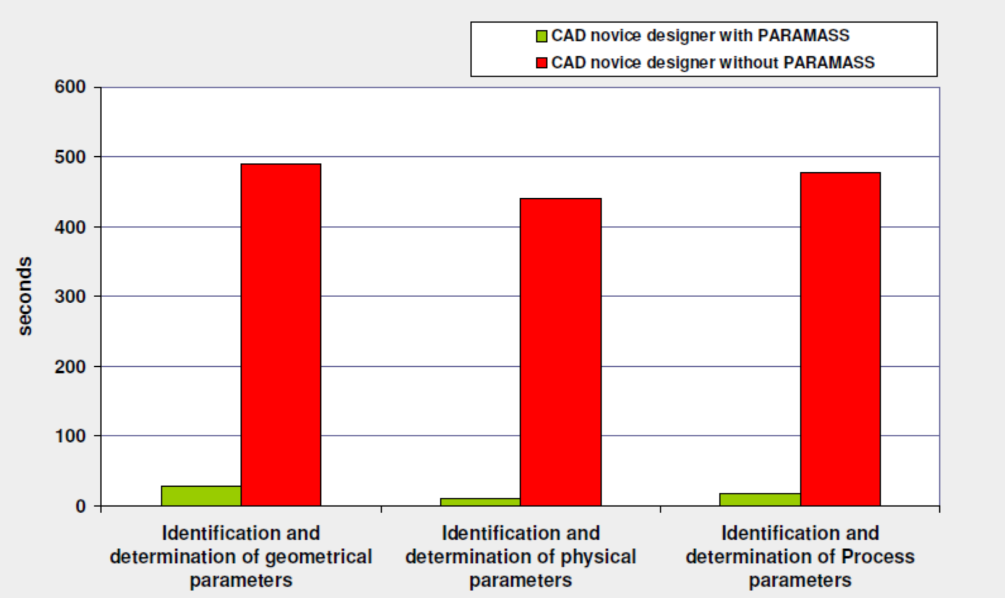

CAD expert designer
CAD novice designer
seconds
310
300
290
280
270
260
250
240
300
263
Identification and determination of associative relationships

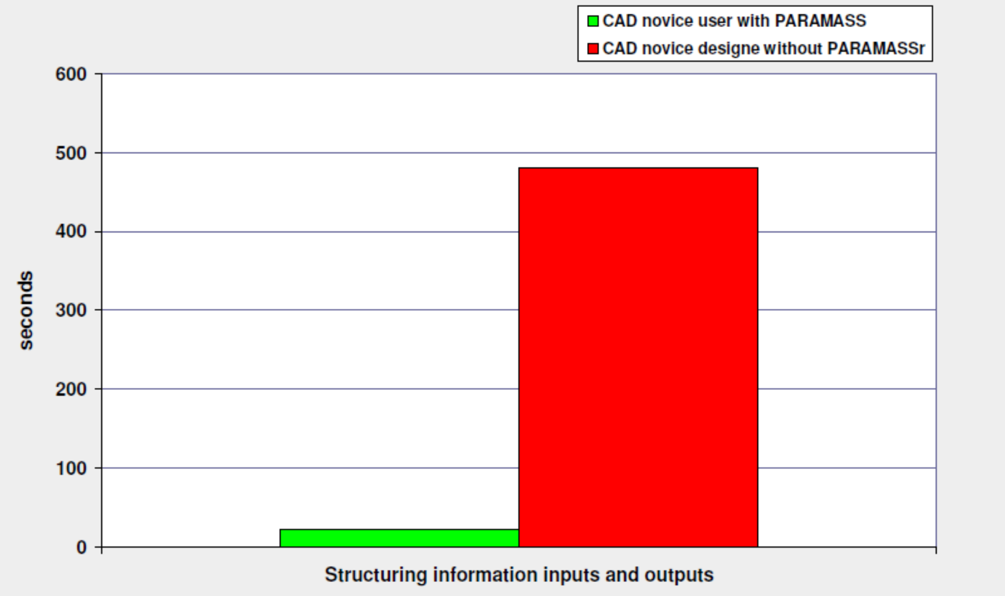

CAD expert designer
CAD novice designer
seconds
600
500
400
300
200
100
0
Structuring information inputs and outputs

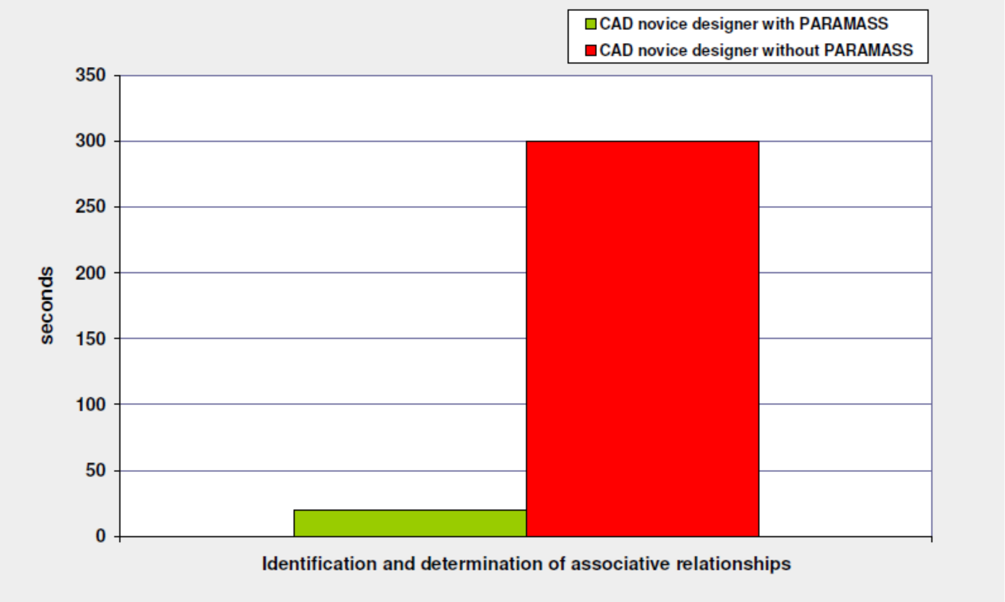

CAD expert designer
CAD novice designer
seconds
30
25
20
15
10
5
0
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters

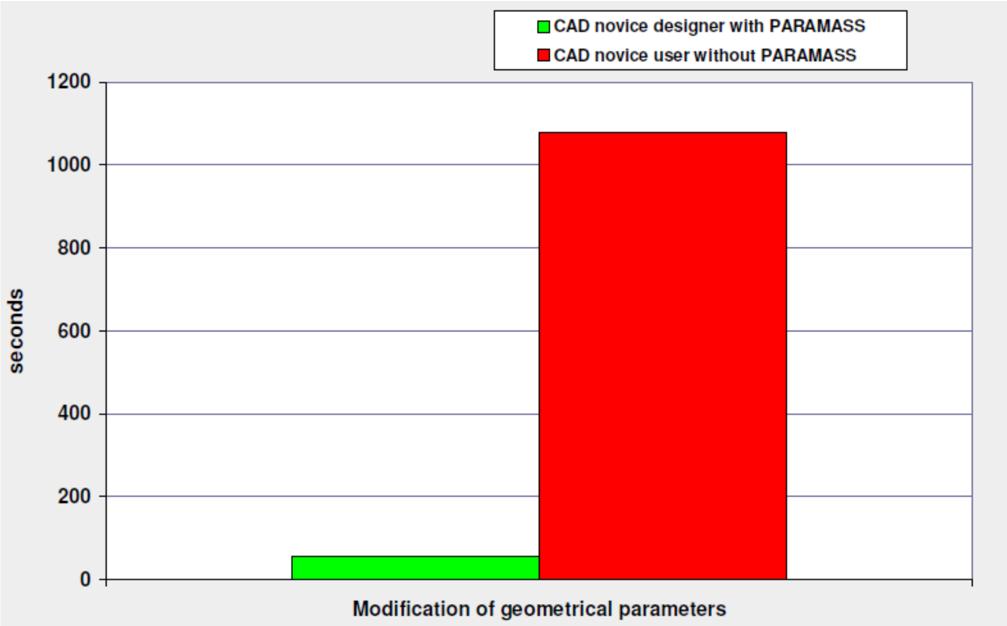

CAD expert designer
CAD novice designer
seconds
25
20
15
10
5
0
Identification and determination of associative relationships

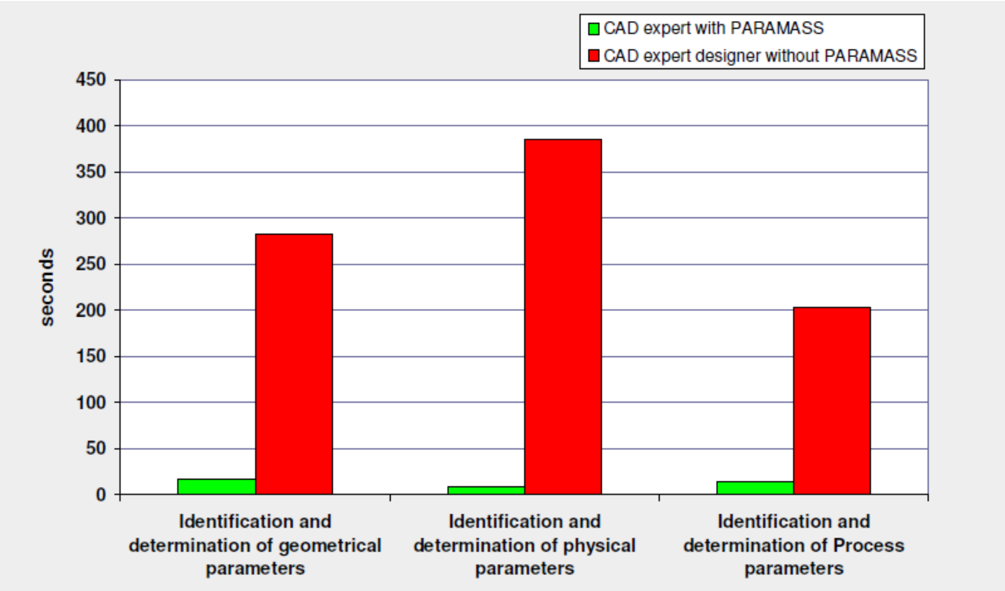

CAD experienced designer
CAD novice designer
seconds
25
20
15
10
5
0
18
22
Structuring information inputs and outputs

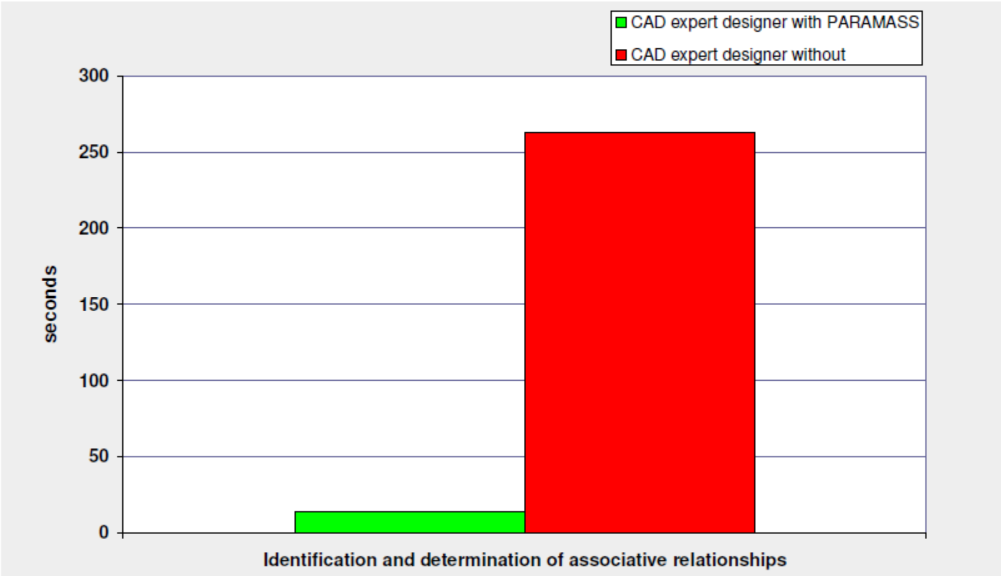

CAD novice designer with PARAMASS
CAD novice designer without PARAMASS
seconds
600
500
400
300
200
100
0
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters

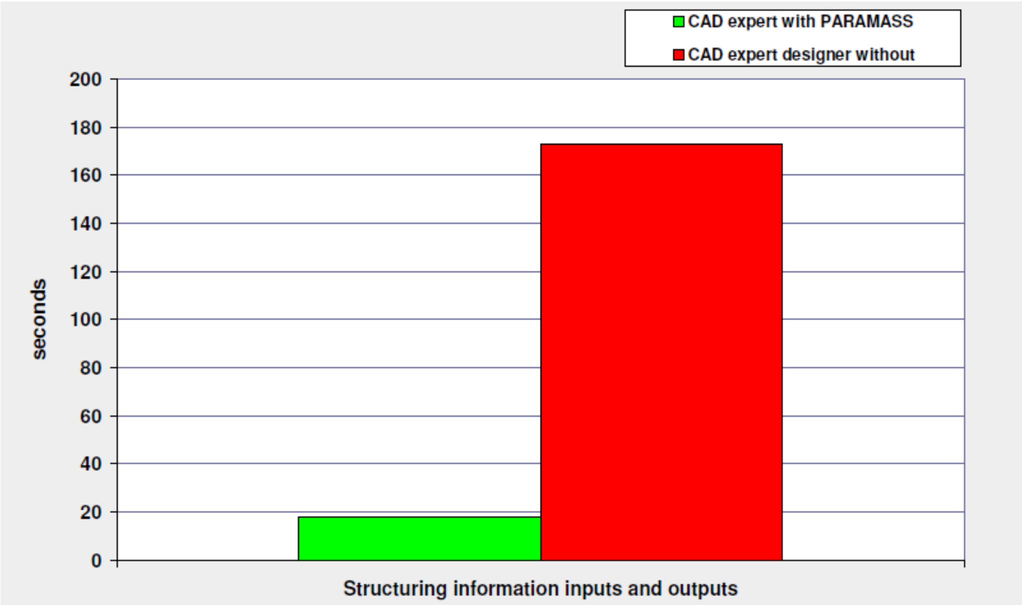

CAD novice user with PARAMASS
CAD novice designe without PARAMASSr
seconds
600
500
400
300
200
100
0
Structuring information inputs and outputs

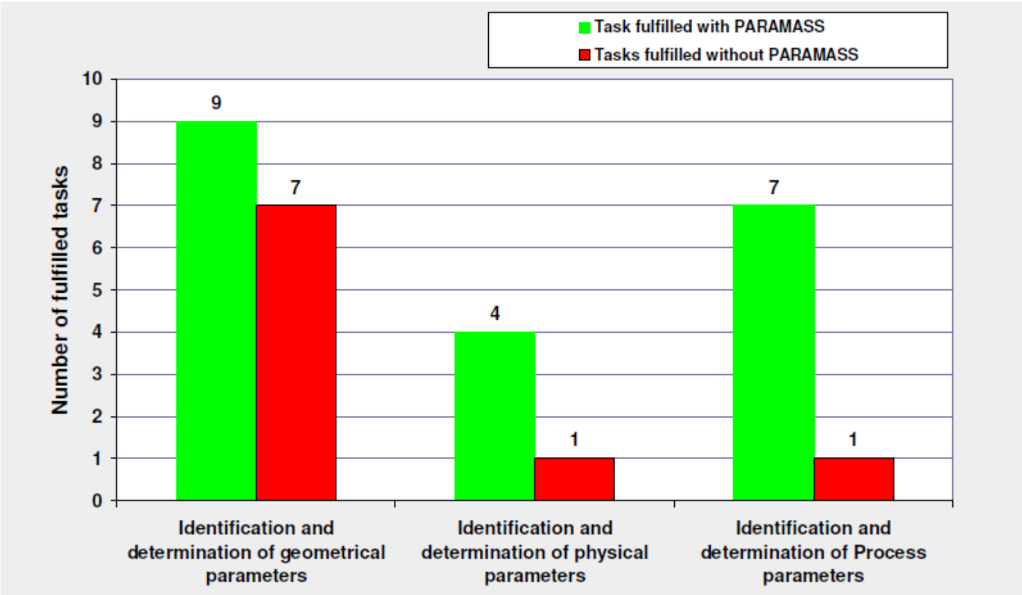

CAD novice designer with PARAMASS
CAD novice designer without PARAMASS
seconds
350
300
250
200
150
100
50
0
Identification and determination of associative relationships

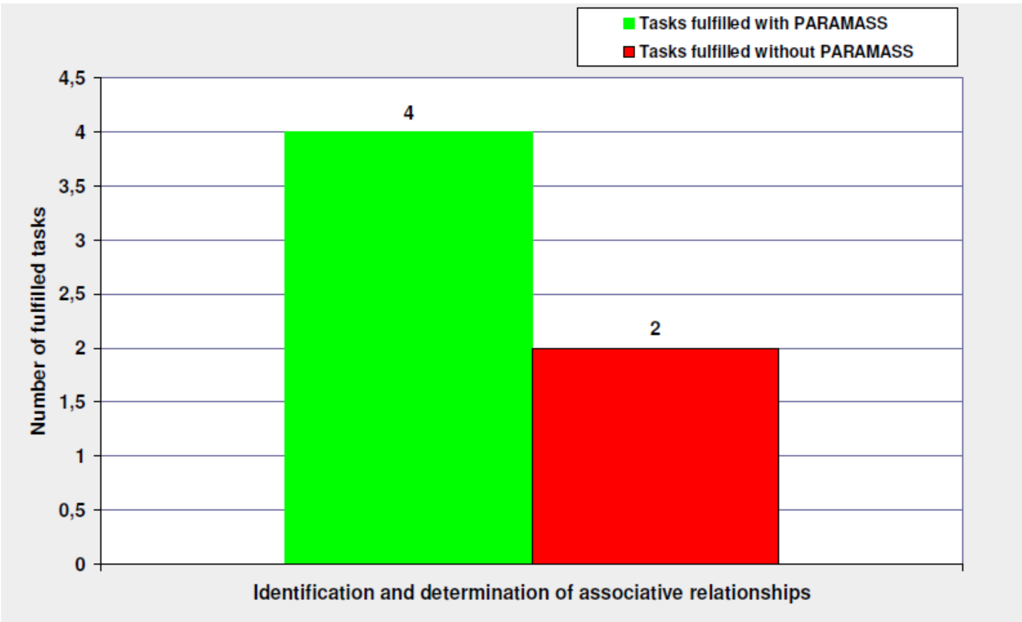

CAD novice designer with PARAMASS
CAD novice user without PARAMASS
seconds
1200
1000
800
600
400
200
0
Modification of geometrical parameters

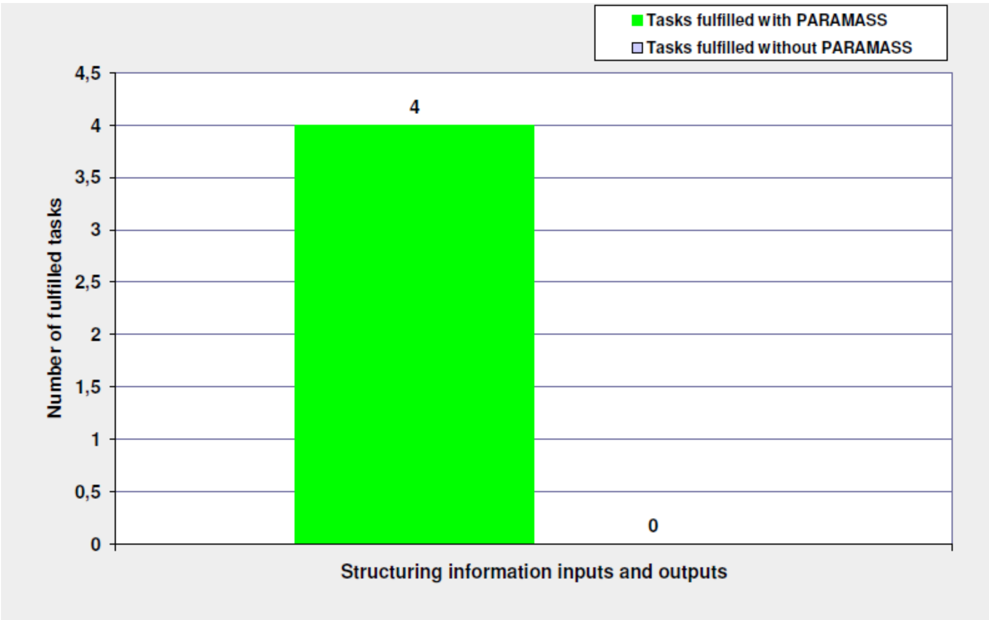

CAD expert with PARAMASS
CAD expert designer without PARAMASS
seconds
450
400
350
300
250
200
150
100
50
0
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters

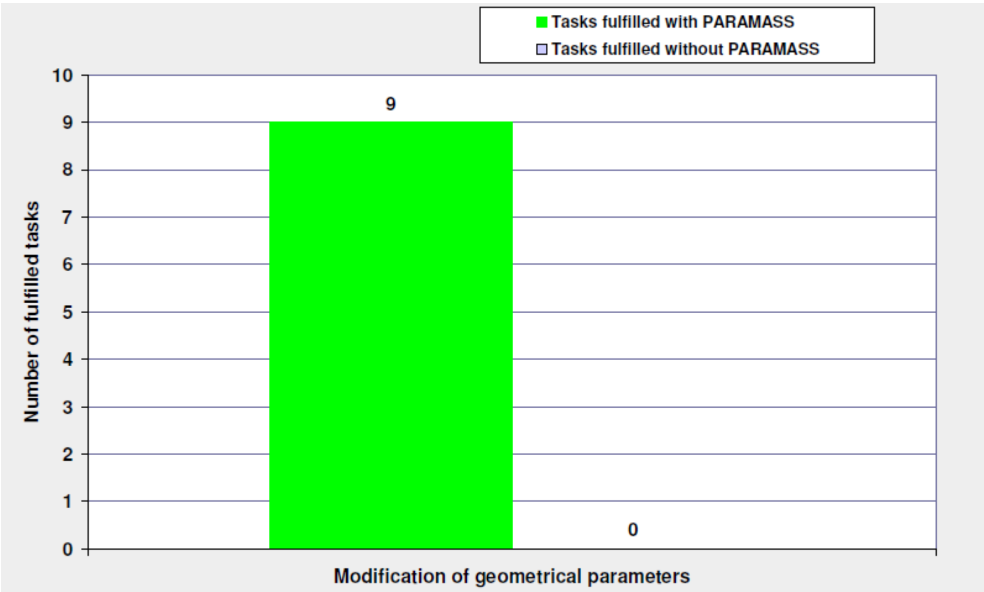

CAD expert designer with PARAMASS
CAD expert designer without
seconds
300
250
200
150
100
50
0
Identification and determination of associative relationships

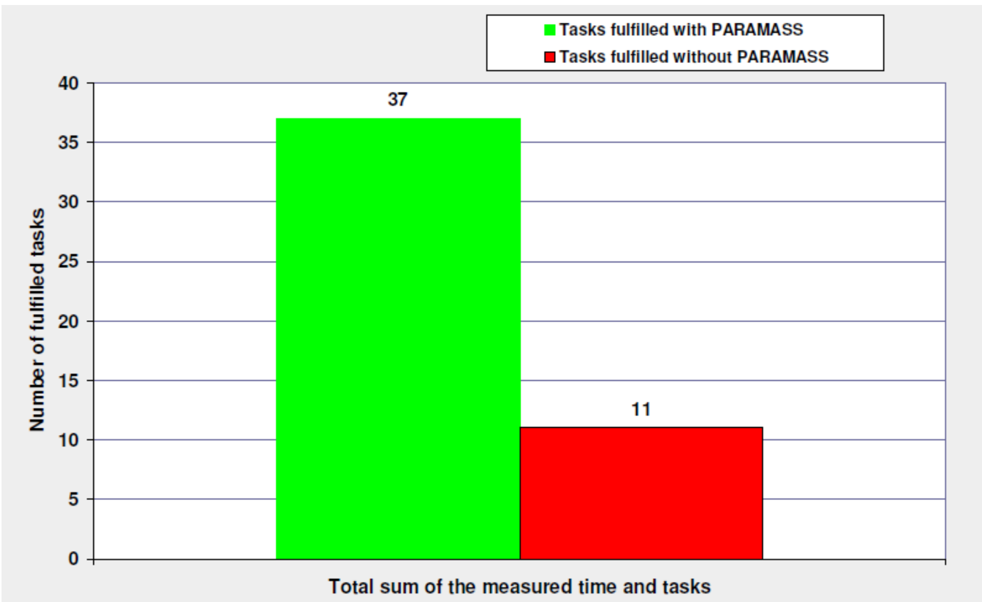

CAD expert with PARAMASS
CAD expert designer without
seconds
200
180
160
140
120
100
80
60
40
20
0
Structuring information inputs and outputs


Task fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
Number of fulfilled tasks
10
9
8
7
6
5
4
3
2
1
0
9
7
4
1
7
1
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters


Tasks fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
Number of fulfilled tasks
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
4
2
Identification and determination of associative relationships


Tasks fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
Number of fulfilled tasks
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
4
0
Structuring information inputs and outputs

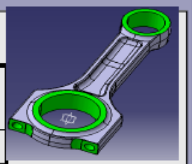

Tasks fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
Number of fulfilled tasks
10
9
8
7
6
5
4
3
2
1
0
9
0
Modification of geometrical parameters


Tasks fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
Number of fulfilled tasks
40
35
30
25
20
15
10
5
0
37
11
Total sum of the measured time and tasks

2) Use Case framework for a connecting rod:

Method Evaluation System (MESY)

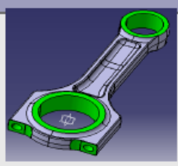
Framework of the use case:



USE CASE NAME: Identification and determination of the conrod parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Identification and determination of the connection rod parameters
Goal of the use case:	Identification and determination of certain parameters
Workflow of the use case:	1. Open the conrod in CATIA V5 (CAD data name: conrod.part). 2. Identify the following parameters: • ***Geometry parameters***:The connection rod length, The diameter of the small connecting rod eye, The diameter of the big connecting rod eye, The diameter of the mounting bold, • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:***
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the conrod part in CATIA V5.
Explanatory notes	The time during the identification of the different parameters will be captured and measured.

Method Evaluation System (MESY)

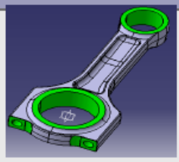
Framework of the use case:



USE CASE NAME: Representation of the relationships between the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Representation of the relationships between the parameters and associative relationships
Goal of the use case:	Identification of certain parameters of the conrod:
Workflow of the use case:	1. Open the conrod in CATIA V5 (CAD data name: conrod.part). 2. Identify the relationships between the following parameters: • ***Geometry parameters***: connection rod length, The diameter of the small connecting rod eye, The diameter of the big connecting rod eye, The diameter of the mounting bold, 3. Close the conrod in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the conrod part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

Method Evaluation System (MESY)

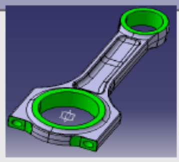
Framework of the use case:



USE CASE NAME: Structuring of the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 2: Identification and determination of information inputs and outputs
Goal of the use case:	Identification of certain parameters of the conrod:
Workflow of the use case:	1. Open the conrod in CATIA V5 (CAD data name: conrod part). 2. Identify the relationships between the following parameters: • ***Geometry parameters***: connection rod length, The diameter of the small connecting rod eye, The diameter of the big connecting rod eye, The diameter of the mounting bold, • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:*** 3. Close the conrod in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the conrod part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

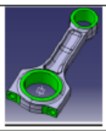
Method Evaluation System (MESY)

Framework of the use case:



USE CASE NAME: Modification of the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 3: Modification of the parameters and associative relationships
Goal of the use case:	Identification of certain parameters of the conrod:
Workflow of the use case:	1. Open the conrod in CATIA V5 (CAD data name: conrod.part). 2. Modification of parameters: • ***Geometry parameters***: connection rod length, The diameter of the small connecting rod eye, The diameter of the big connecting rod eye, The diameter of the mounting bold, 3. Close the conrod in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the conrod part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

Use case measurement protocol
CONNECTION ROD

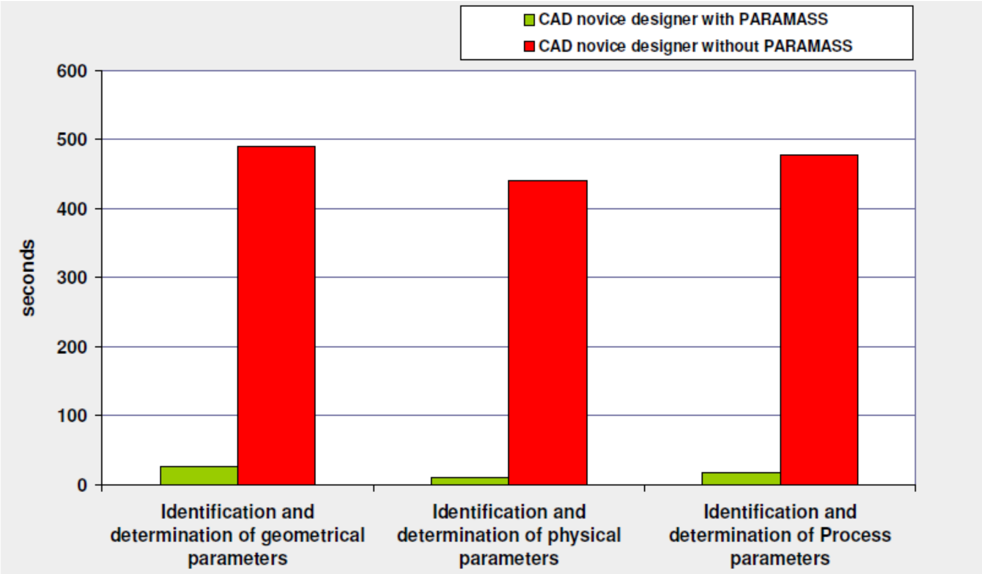
Use case name: Identification and determination of the connection rod parameters and associative relationships	
Use case number: 2	
Level of the use case: Evaluation of phase I, II and III of the developed method	
Date: 01.05.2009	
Designer/Design group: with or without the method	

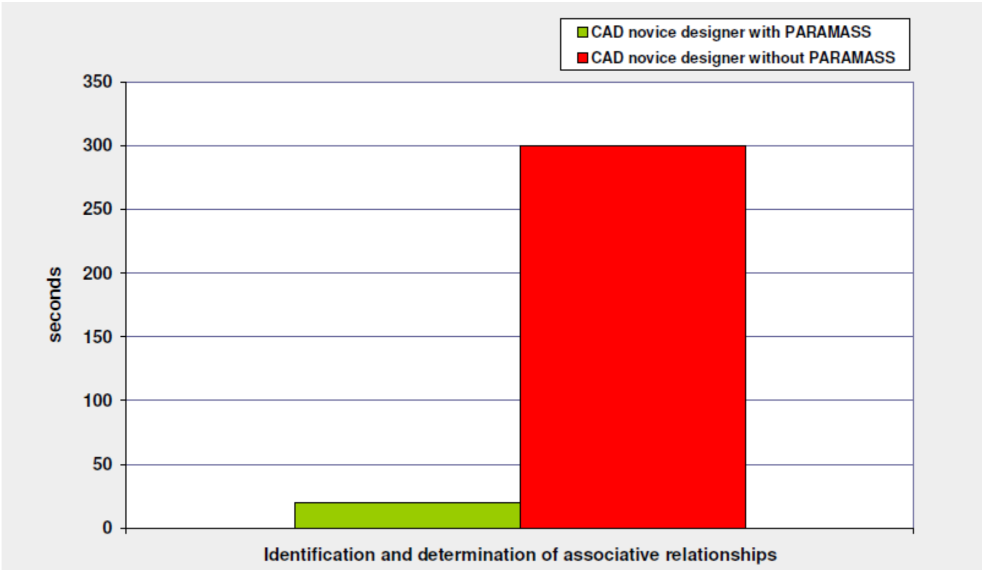
	With the PARAMASS approach		Without PARAMASS approach	
Phase 1: Identification and determination of parameters and associativity	Time (Minutes/ seconds)	Task fulfilled No○/Yes●	Time (Minutes/se conds)	Task fulfilled No○/Yes●
Geometrical parameters:				
The connection rod length:				
The diameter of the small connecting rod eye:				
The diameter of the big connecting rod eye:				
The diameter of the mounting bold:				
Sum of the measured time and tasks				
Physical parameters:				
The connection rod mass:				
The connection rod material:				
The connection rod center of gravity:				
The connection rod inertia tensor:				
Sum of the measured time and tasks				
Process parameters:				
The rough part of the connection rod:				
The finish part of the connection rod:				
The position of the small connection rod eye:				
The position of the big connection rod:				
The finish surface of the small connection rod:				
The finish surface of the big connection rod:				
The machining tolerances of the small connection rod				
Tolerances of axis parallelism of the small and big connection rod eye:				
Sum of the measured time and tasks				

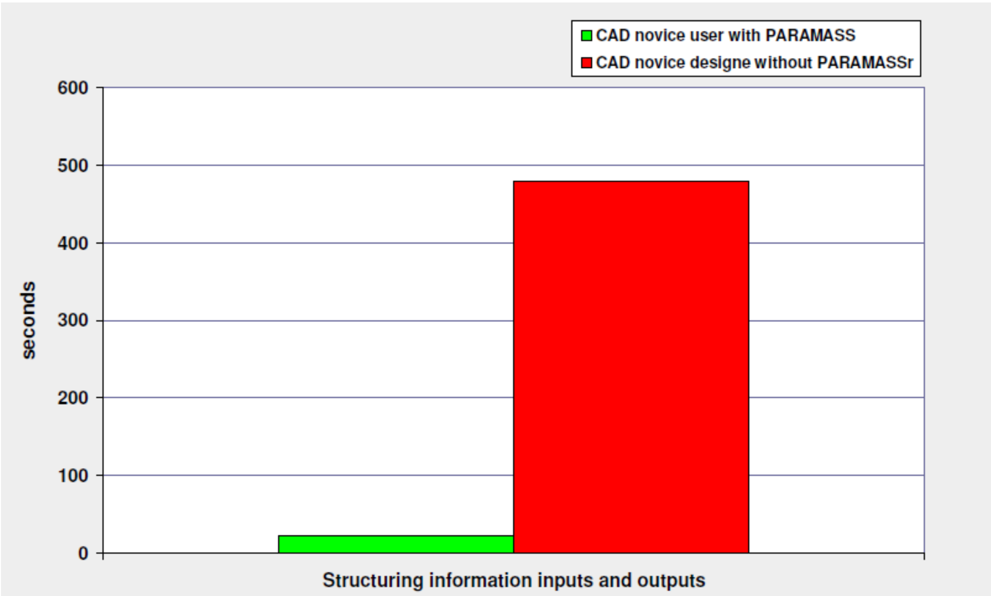
	With the PARAMASS approach		Without PARAMASS approach	
Phase 1: Identification and determination of parameters and associativity	Time (Minutes/ seconds)	Task fulfilled No○/Yes●	Time (Minutes/se conds)	Task fulfilled No○/Yes●
Associative relationship				
The connection rod position:				
The connection rod axis:				
The connection geometry between connection rod and the crankshaft:				
The connection rod drawing:				
Sum of the measured time and tasks				

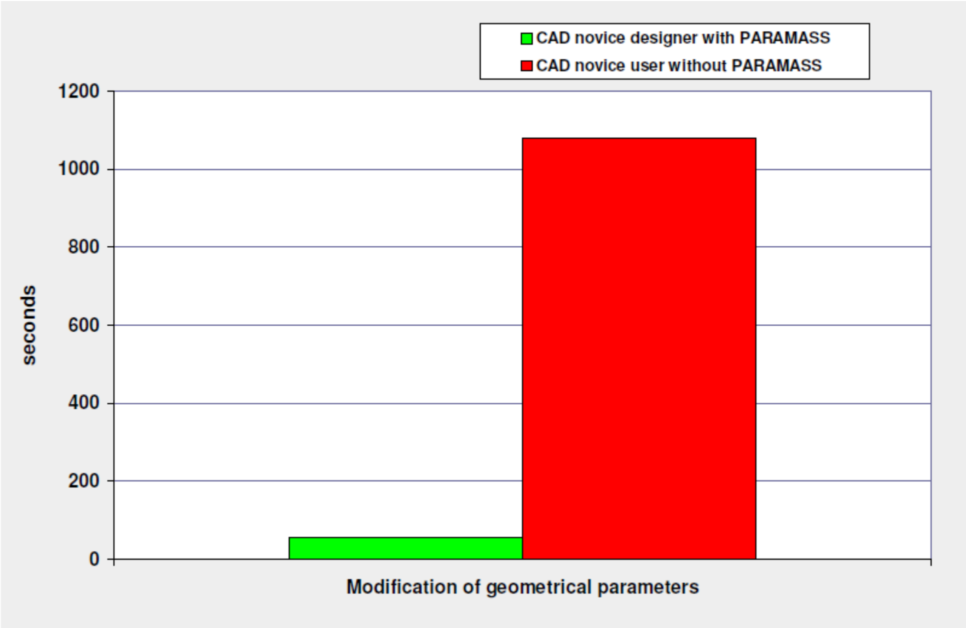
	With the PARAMASS approach		Without PARAMASS approach	
Phase 2: Structuring and creation phase	Time (Minutes/ seconds)	Task fulfilled No○/Yes●	Time (Minutes/se conds)	Task fulfilled No○/Yes●
Identify and determine the parts structure (rough-part and finish-part)				
Identify and determine the design information inputs				
Identify and determine the design information outputs				
Identify and determine the relevant reference geometry of the skeleton models:				
Sum of the measured time and tasks				
Phase 3: Modification phase (modify the following parameters and associative relationships)	Time (Minutes/ seconds)	Task fulfilled No○/Yes●	Time (Minutes/se conds)	Task fulfilled No○/Yes●
The connection rod length:				
The diameter of the small connecting rod eye:				
The diameter of the big connecting rod eye:				
The diameter of the mounting bold:				
Sum of the measured time and tasks				
Total sum of the measured time and tasks				

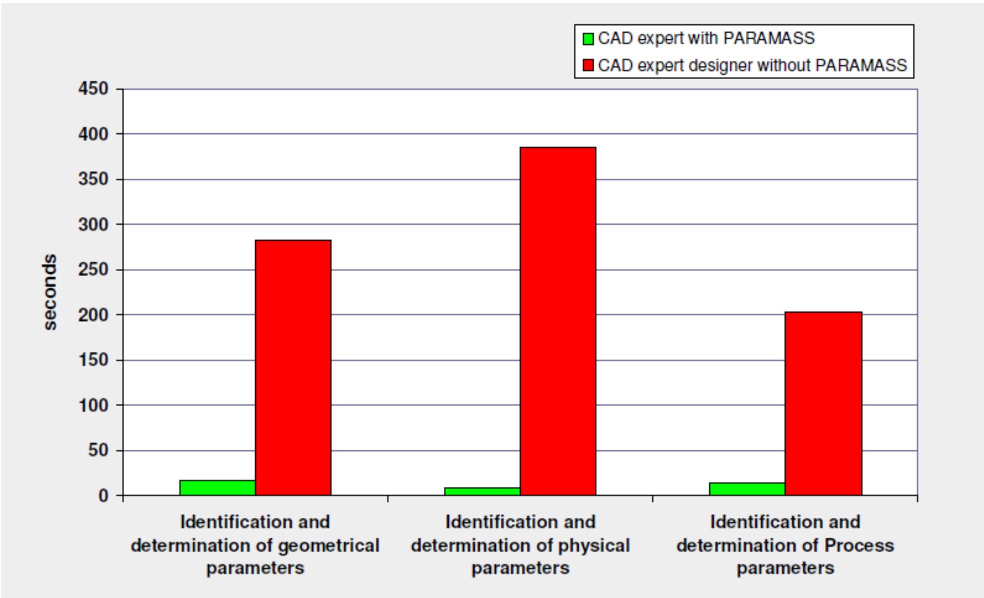
Results of the Use Cases for the connecting rod:

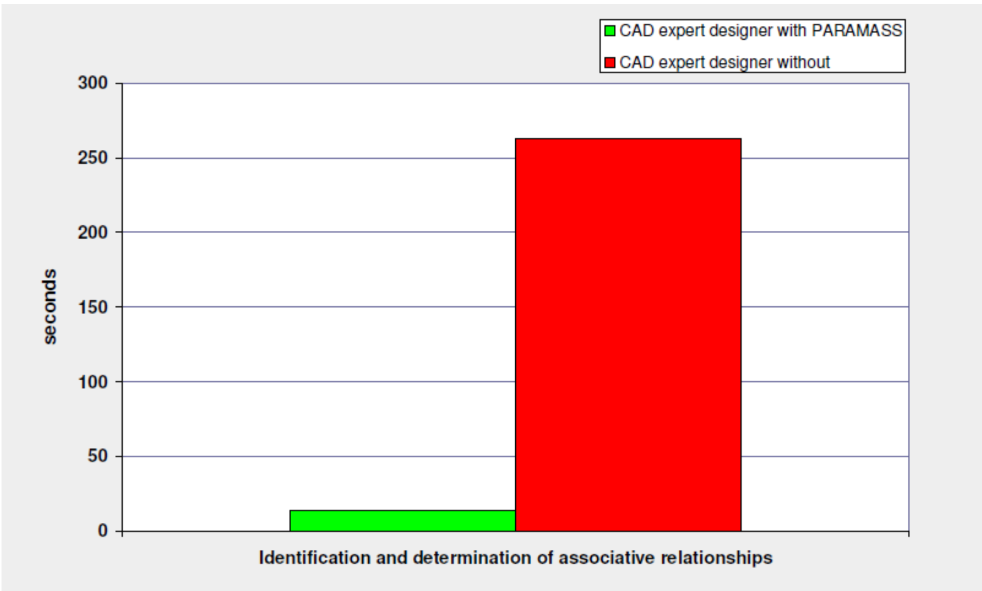


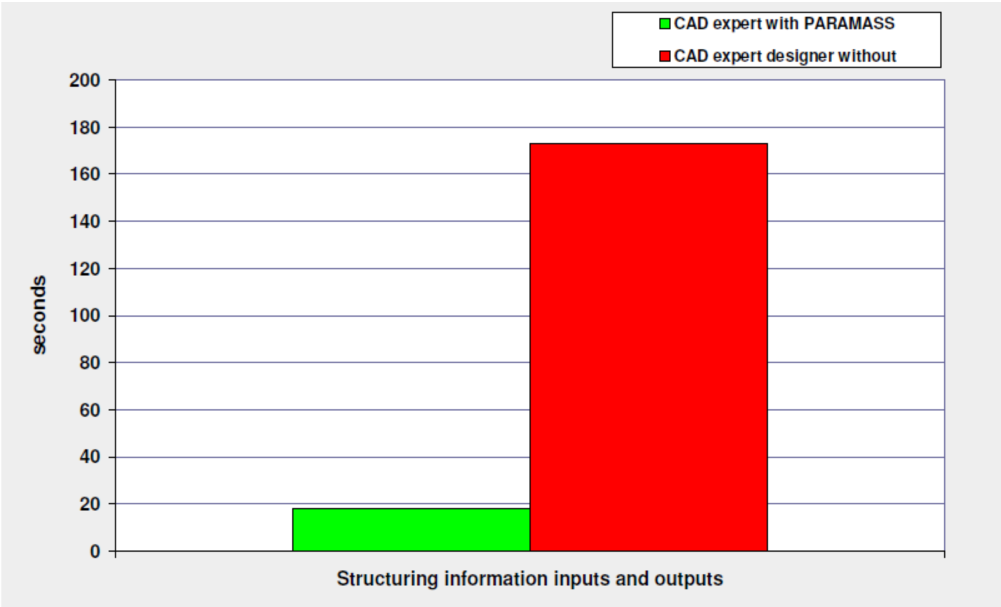




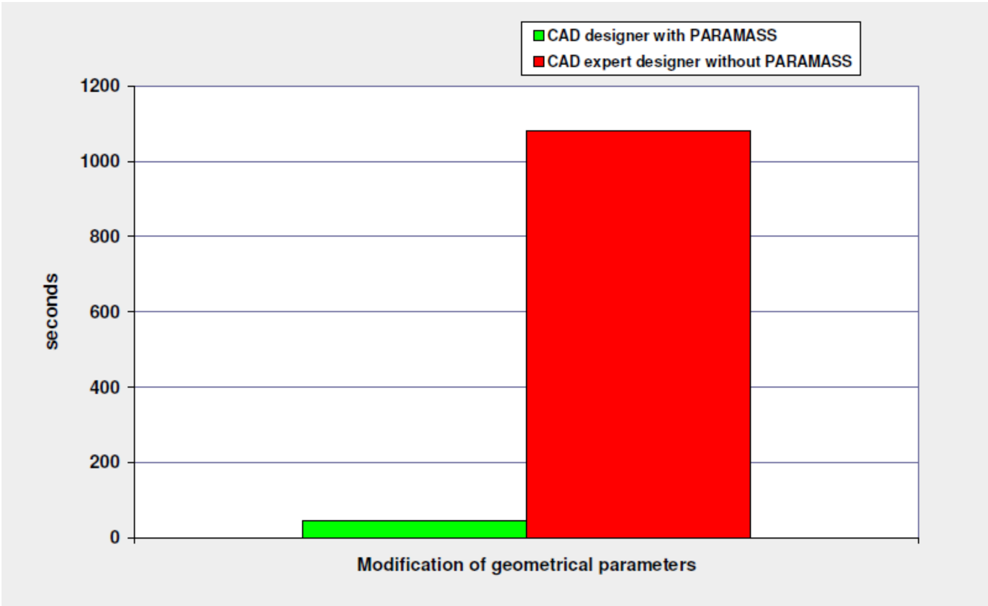

CAD novice designer with PARAMASS
CAD novice user without PARAMASS
seconds
1200
1000
800
600
400
200
0
Modification of geometrical parameters


CAD expert with PARAMASS
CAD expert designer without PARAMASS
seconds
450
400
350
300
250
200
150
100
50
0
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters

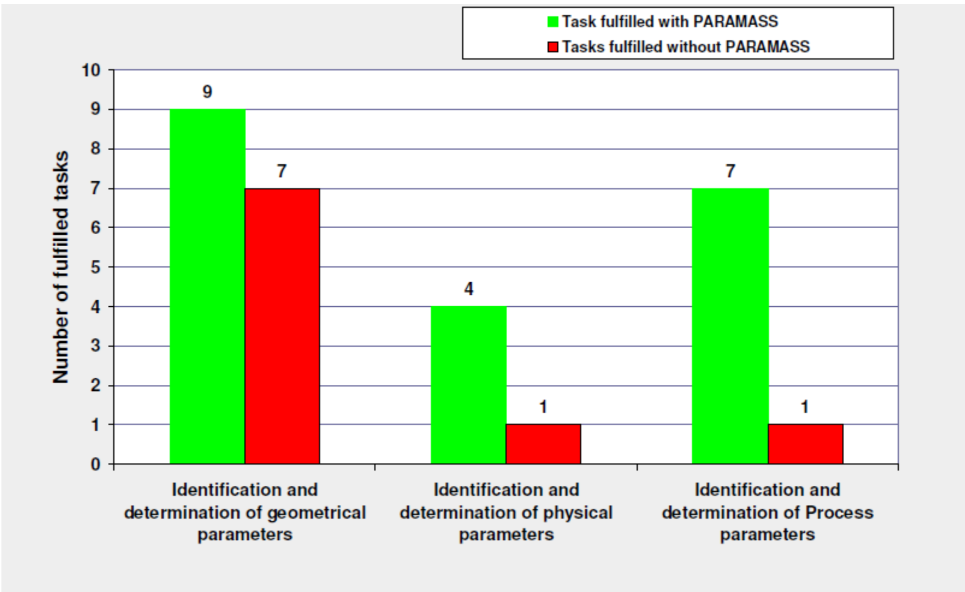

CAD expert designer with PARAMASS
CAD expert designer without
seconds
300
250
200
150
100
50
0
Identification and determination of associative relationships



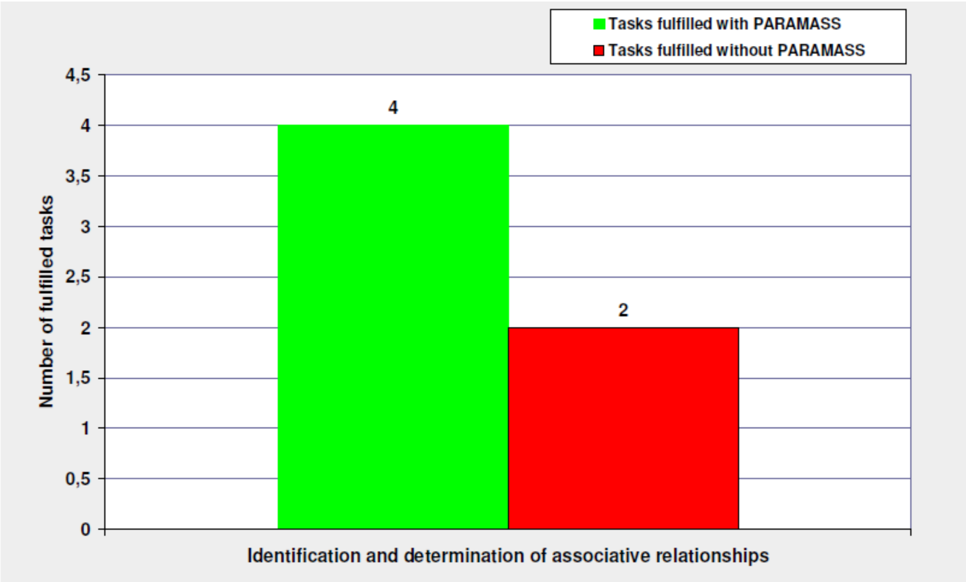
CAD expert with PARAMASS
CAD expert designer without
200
180
160
140
120
100
80
60
40
20
0
seconds
Structuring information inputs and outputs

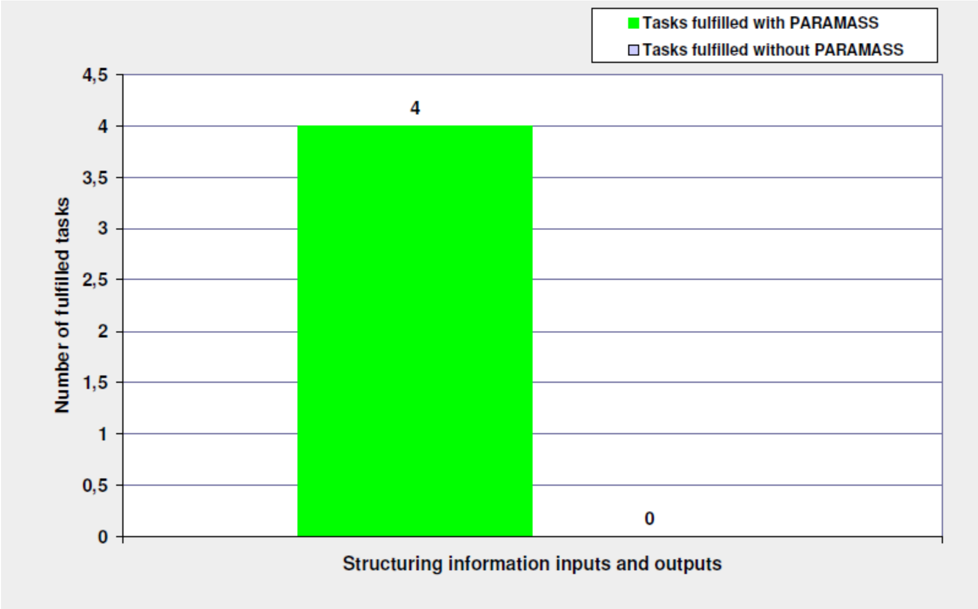


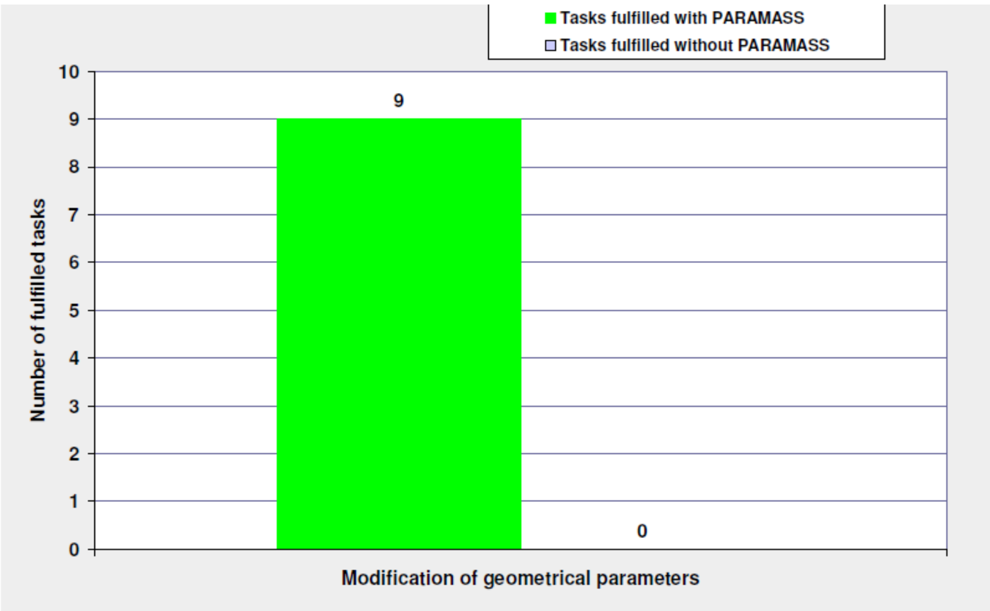
CAD designer with PARAMASS
CAD expert designer without PARAMASS
1200
1000
800
600
400
200
0
seconds
Modification of geometrical parameters

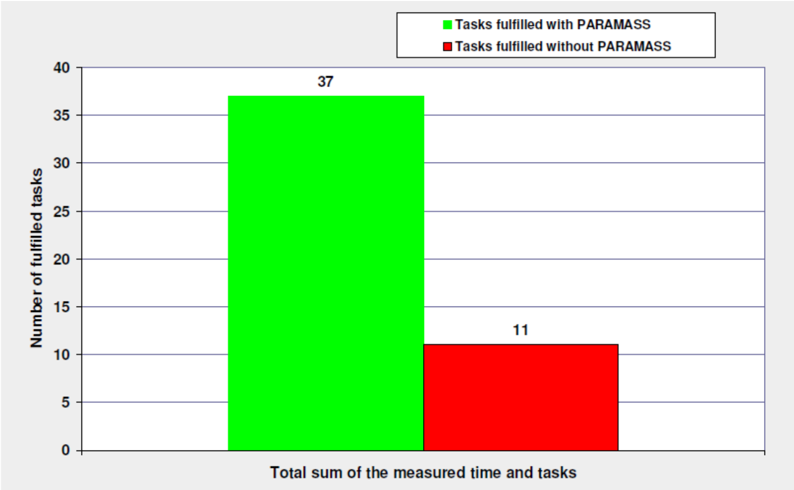


Task fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
10
9
8
7
6
5
4
3
2
1
0
Number of fulfilled tasks
9
7
4
1
7
1
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters

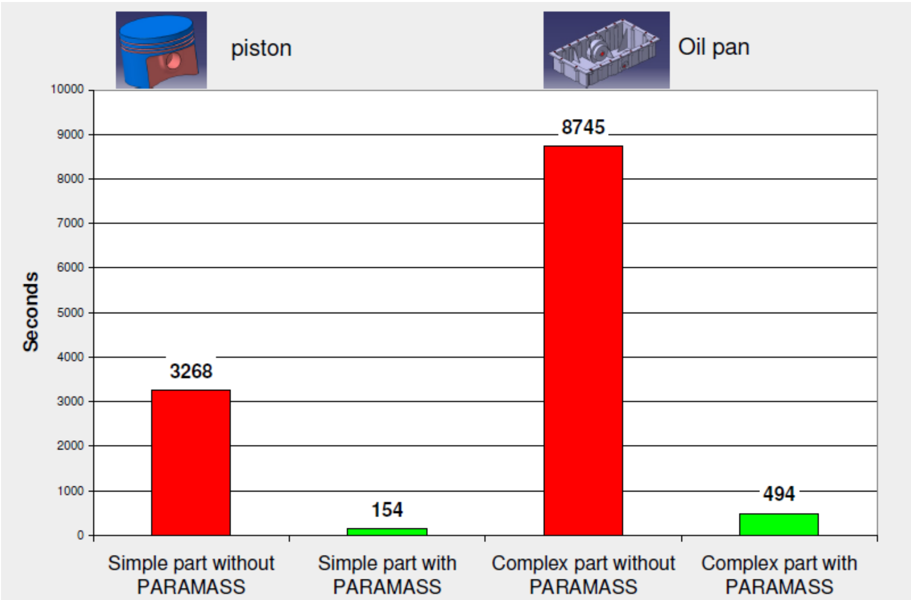

Tasks fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
Number of fulfilled tasks
4
2
Identification and determination of associative relationships

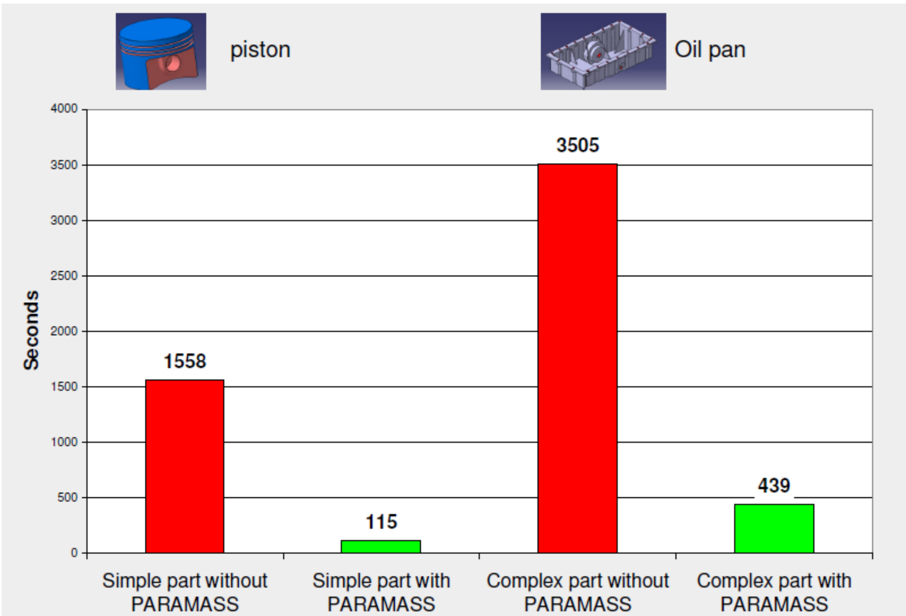

Tasks fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
Number of fulfilled tasks
4
0
Structuring information inputs and outputs

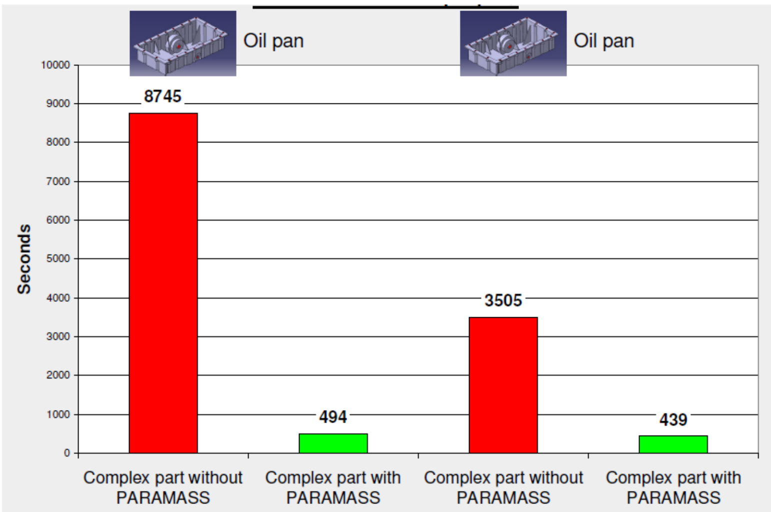

Tasks fulfilled with PARAMASS
Tasks fulfilled without PARAMASS
10
9
8
7
6
5
4
3
2
1
0
Number of fulfilled tasks
9
0
Modification of geometrical parameters



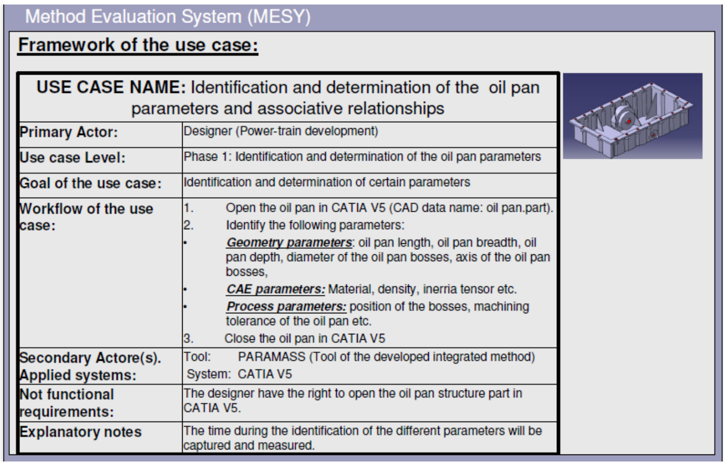
Comparison of the Use Cases of the piston and oil pan:







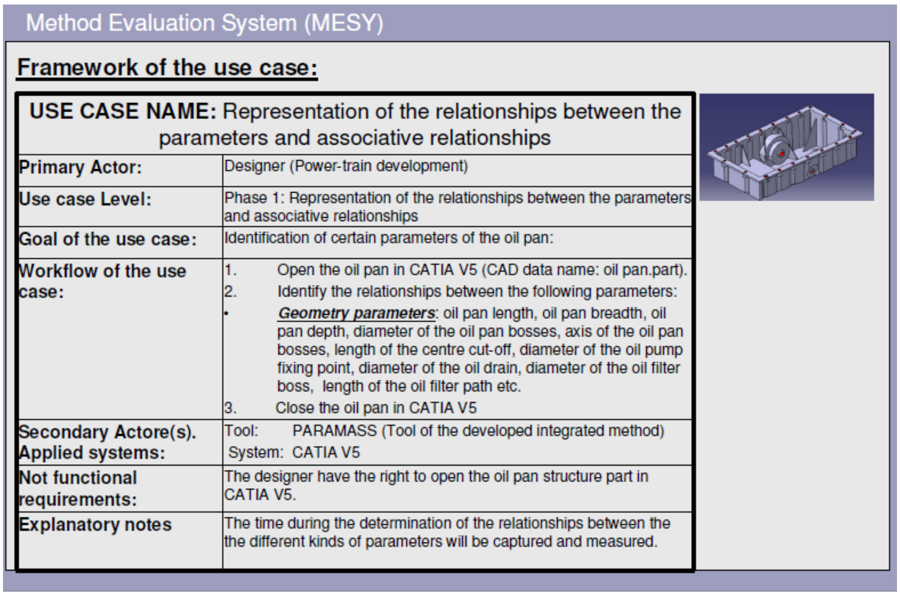
3) Use Case framework for an oil pan:



Method Evaluation System (MESY)

Framework of the use case:

USE CASE NAME: Identification and determination of the oil pan parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Identification and determination of the oil pan parameters
Goal of the use case:	Identification and determination of certain parameters
Workflow of the use case:	1. Open the oil pan in CATIA V5 (CAD data name: oil pan.part). 2. Identify the following parameters: • ***Geometry parameters***: oil pan length, oil pan breadth, oil pan depth, diameter of the oil pan bosses, axis of the oil pan bosses, • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:*** position of the bosses, machining tolerance of the oil pan etc. 3. Close the oil pan in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the oil pan structure part in CATIA V5.
Explanatory notes	The time during the identification of the different parameters will be captured and measured.



Method Evaluation System (MESY)

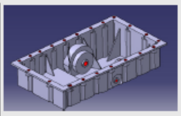
Framework of the use case:

USE CASE NAME: Representation of the relationships between the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Representation of the relationships between the parameters and associative relationships
Goal of the use case:	Identification of certain parameters of the oil pan:
Workflow of the use case:	1. Open the oil pan in CATIA V5 (CAD data name: oil pan.part). 2. Identify the relationships between the following parameters: • ***Geometry parameters***: oil pan length, oil pan breadth, oil pan depth, diameter of the oil pan bosses, axis of the oil pan bosses, length of the centre cut-off, diameter of the oil pump fixing point, diameter of the oil drain, diameter of the oil filter boss, length of the oil filter path etc. 3. Close the oil pan in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the oil pan structure part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

Method Evaluation System (MESY)

Framework of the use case:

USE CASE NAME: Structuring of the parameters and associative relationships

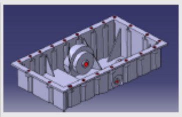


Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 2: Identification and determination of information inputs and outputs
Goal of the use case:	Identification of certain parameters of the piston:
Workflow of the use case:	1. Open the oil pan in CATIA V5 (CAD data name: oil pan. part). 2. Identify the relationships between the following parameters: • ***Geometry parameters***: oil pan length, oil pan breadth, oil pan depth, diameter of the oil pan bosses etc. • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:*** position of the bosses, tolerance of the oil pan machining. 3. Close the oil pan in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the oil pan structure part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

Method Evaluation System (MESY)

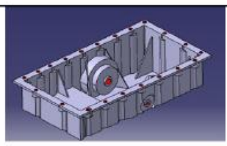
Framework of the use case:

USE CASE NAME: Modification of the parameters and associative relationships



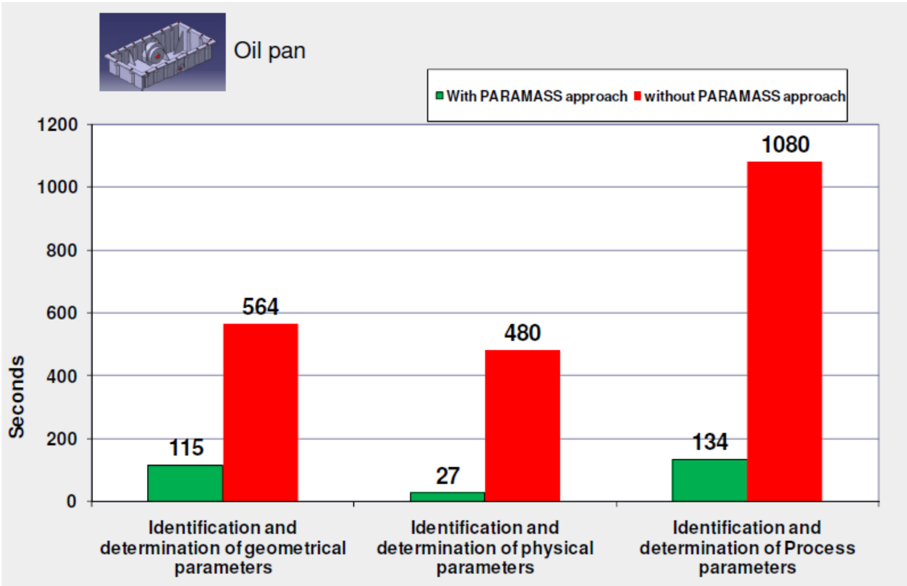
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 3: Modification of the parameters and associative relationships
Goal of the use case:	Identification of certain parameters of the oil pan:
Workflow of the use case:	1. Open the piston in CATIA V5 (CAD data name: oil pan.part). 2. Modification of parameters: • ***Geometry parameters***: oil pan length, oil pan breadth, oil pan depth, diameter of the oil pan bosses, axis of the oil pan bosses, length of the centre cut-off, diameter of the oil pump fixing point, diameter of the oil drain, diameter of the oil filter boss, length of the oil filter path etc. 3. Close the oil pan in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the oil pan part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

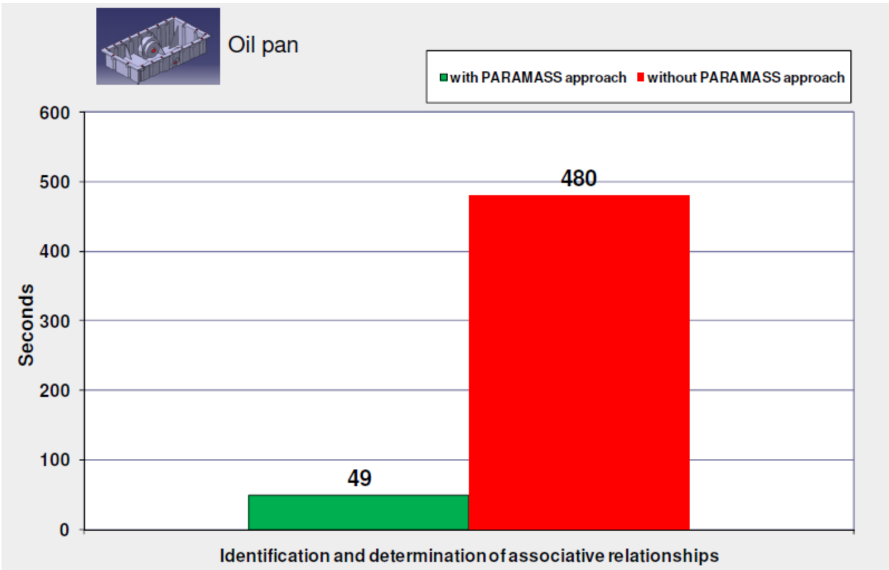
Use case measurement protocol
Oil pan

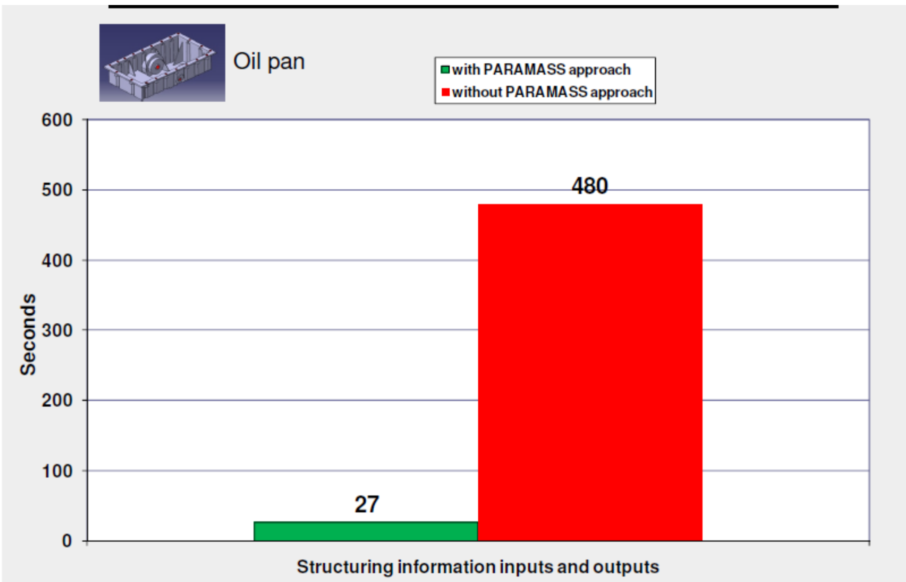
Use case name: Identification and determination of the oil pan parameters and associative relationships	
Use case number: 3	
Level of the use case: Evaluation of phase I , II and III of the developed method	
Date: 01.05.2009	
Designer/Design group: with or without the method	

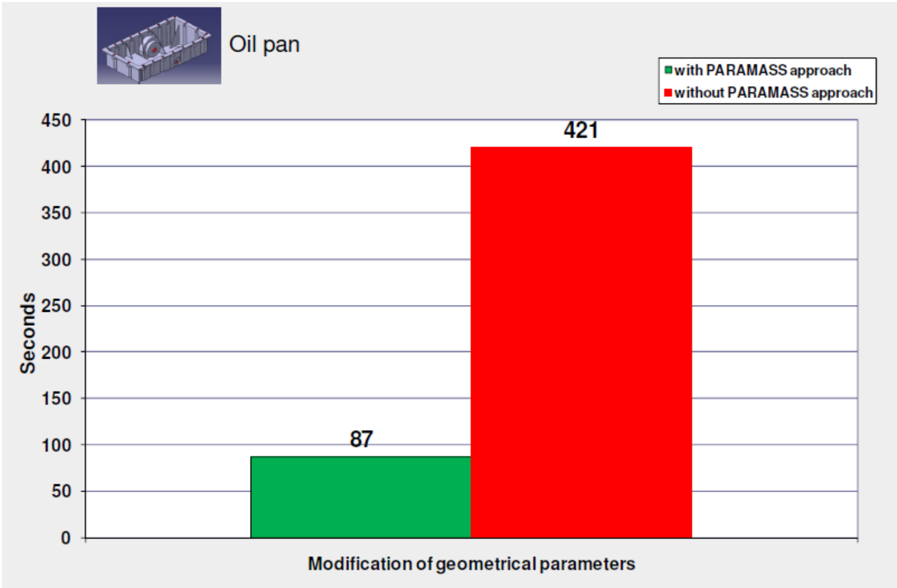
	With the PARAMASS approach		Without PARAMASS approach	
Phase 1: Identification and determination of parameters and associativity	Time (Minutes/ seconds)	Task fulfilled No☐/Yes●	Time (Minutes/seconds)	Task fulfilled No☐/Yes●
Geometrical parameters:				
The oil pan length:				
The oil pan breadth:				
The oil pan depth:				
The diameter of the oil pan bosses:				
The axis of the oil pan bosses:				
The length of the centre cut-off:				
The diameter of the oil pump fixing point:				
The diameter of the oil drain:				
The diameter of the oil filter boss:				
The length of the oil filter path:				
The position of oil pan boss 1				
The axis of oil pan boss 1				
The diameter of oil pan boss 1				
The position of oil pan boss 10				
The axis of oil pan boss 10				
The diameter of oil pan boss 10				
The position of oil pan boss 16				
The axis of oil pan boss 16				
The diameter of oil pan boss 16				
Sum of the measured time and tasks				
Physical parameters:				
The oil pan mass:				
The oil pan material:				
The oil pan center of gravity:				

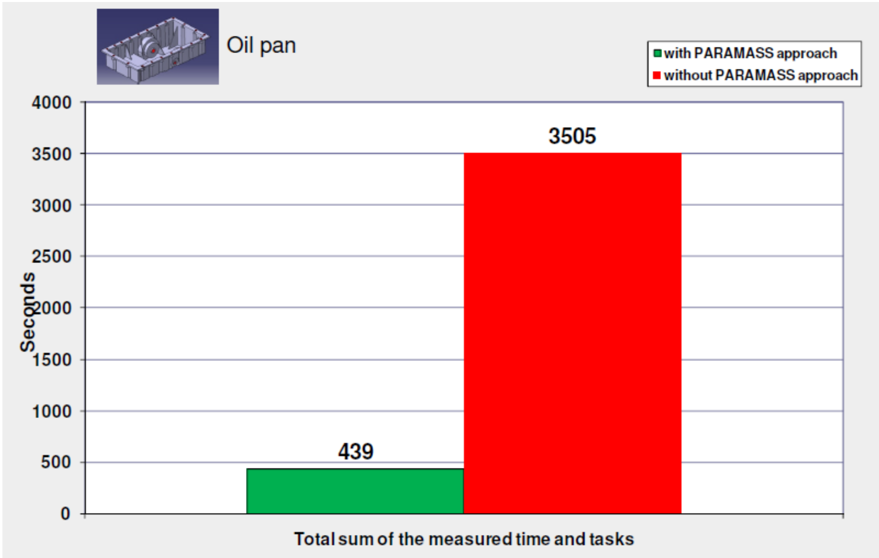
Results of the Use Cases for the oil pan:

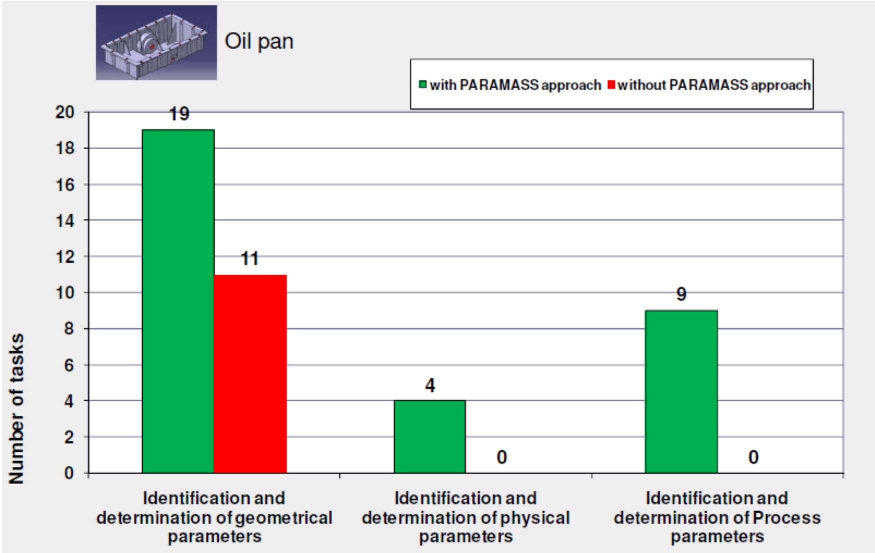

Oil pan
With PARAMASS approach
without PARAMASS approach
Seconds
1200
1000
800
600
400
200
0
115
564
27
480
134
1080
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters

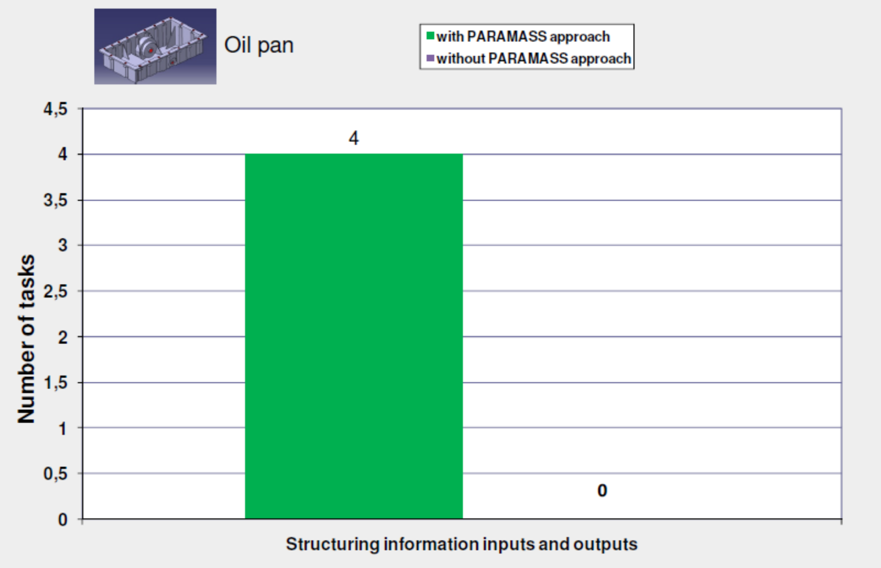

Oil pan
with PARAMASS approach
without PARAMASS approach
Seconds
600
500
400
300
200
100
0
49
480
Identification and determination of associative relationships

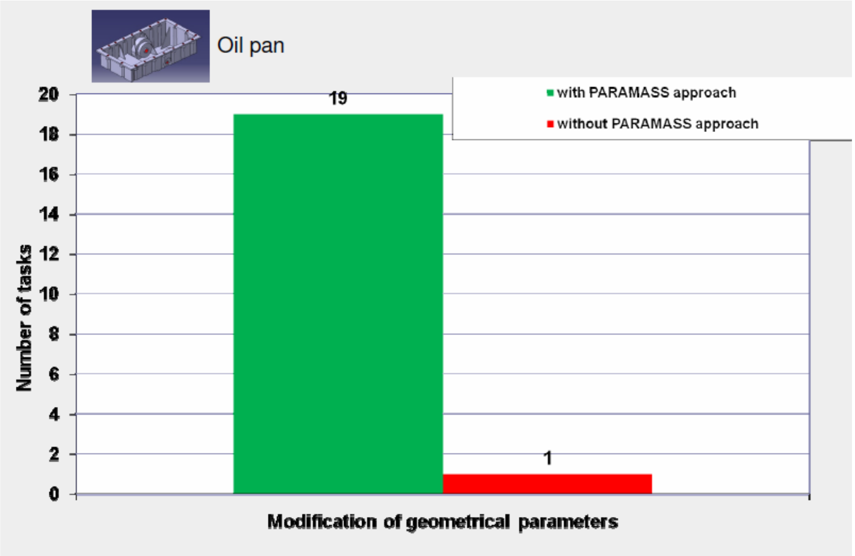

Oil pan
with PARAMASS approach
without PARAMASS approach
Seconds
600
500
400
300
200
100
0
27
480
Structuring information inputs and outputs

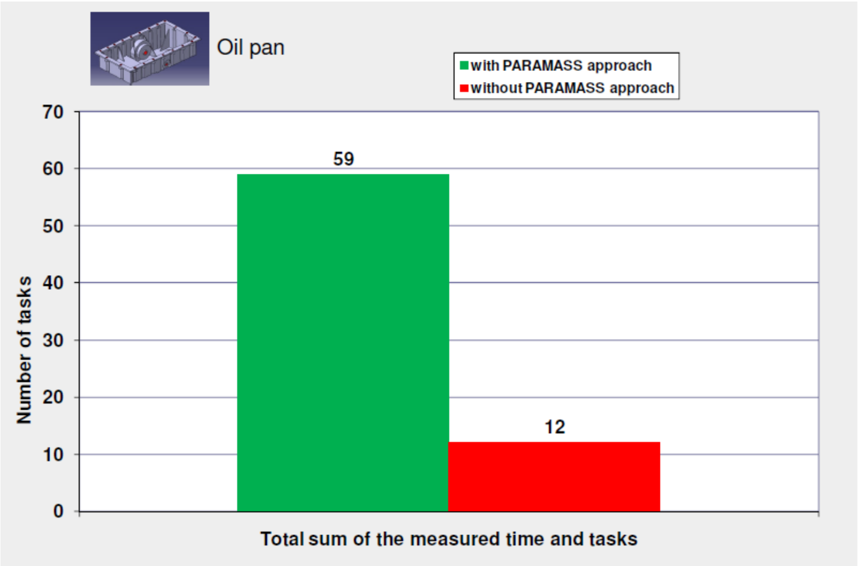

Oil pan
with PARAMASS approach
without PARAMASS approach
Seconds
450
400
350
300
250
200
150
100
50
0
87
421
Modification of geometrical parameters


Oil pan
with PARAMASS approach
without PARAMASS approach
Seconds
4000
3500
3000
2500
2000
1500
1000
500
0
439
3505
Total sum of the measured time and tasks


Oil pan
with PARAMASS approach
without PARAMASS approach
Number of tasks
20
18
16
14
12
10
8
6
4
2
0
19
11
4
0
9
0
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters



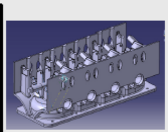




4) Use Case framework for a cylinder head:

Method Evaluation System (MESY)

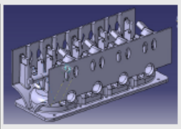
Framework of the use case:



USE CASE NAME: Identification and determination of the cylinder head parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Identification and determination of the cylinder head parameters
Goal of the use case:	Identification and determination of certain parameters
Workflow of the use case:	1. Open the oil pan in CATIA V5 (CAD data name: cylinder head.part). 2. Identify the following parameters: • ***Geometry parameters***: diameter of the cylinder bore, diameter of the inlet valve, centre of the inlet valve, axis of the inlet valve, inlet valve plane etc. • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:*** position of the bosses, machining tolerance of the cylinder head etc. 3. Close the cylinder head in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the cylinder head structure part in CATIA V5.
Explanatory notes	The time during the identification of the different parameters will be captured and measured.

Method Evaluation System (MESY)

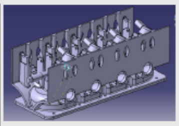
Framework of the use case:



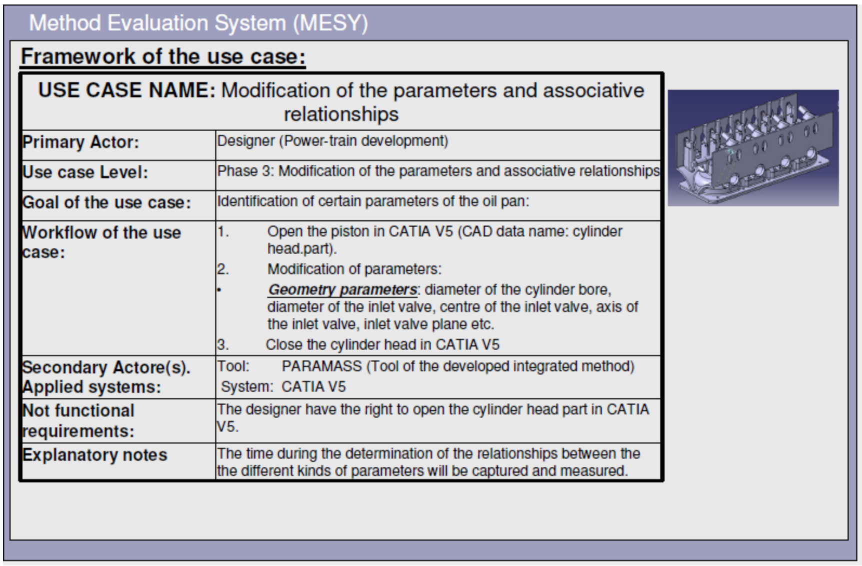
USE CASE NAME: Representation of the relationships between the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 1: Representation of the relationships between the parameters and associative relationships
Goal of the use case:	Identification of certain parameters of the cylinder head:
Workflow of the use case:	1. Open the oil pan in CATIA V5 (CAD data name: cylinder head.part). 2. Identify the relationships between the following parameters: • ***Geometry parameters***: diameter of the cylinder bore, diameter of the inlet valve, centre of the inlet valve, axis of the inlet valve, inlet valve plane etc. 3. Close the cylinder head in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the cylinder head structure part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

Method Evaluation System (MESY)

Framework of the use case:



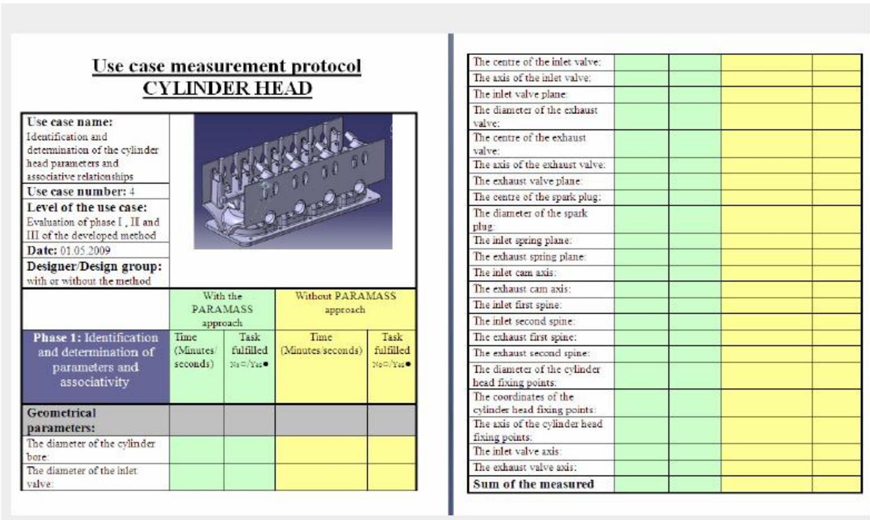
USE CASE NAME: Structuring of the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 2: Identification and determination of information inputs and outputs
Goal of the use case:	Identification of certain parameters of the cylinder head:
Workflow of the use case:	1. Open the oil pan in CATIA V5 (CAD data name: cylinder head. part). 2. Identify the relationships between the following parameters: • ***Geometry parameters***: diameter of the cylinder bore, diameter of the inlet valve, centre of the inlet valve, axis of the inlet valve, inlet valve plane etc. • ***CAE parameters:*** Material, density, inerria tensor etc. • ***Process parameters:*** position of the bosses, tolerance of the cylinder head machining. 3. Close the cylinder headin CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the cylinder head structure part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.



Method Evaluation System (MESY)

Framework of the use case:

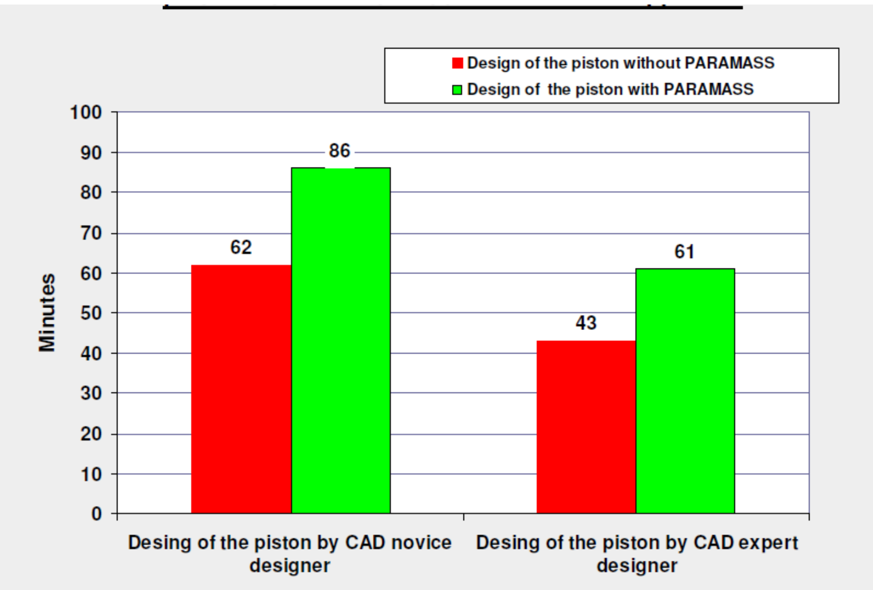
USE CASE NAME: Modification of the parameters and associative relationships	
Primary Actor:	Designer (Power-train development)
Use case Level:	Phase 3: Modification of the parameters and associative relationships
Goal of the use case:	Identification of certain parameters of the oil pan:
Workflow of the use case:	1. Open the piston in CATIA V5 (CAD data name: cylinder head.part). 2. Modification of parameters: • ***Geometry parameters***: diameter of the cylinder bore, diameter of the inlet valve, centre of the inlet valve, axis of the inlet valve, inlet valve plane etc. 3. Close the cylinder head in CATIA V5
Secondary Actore(s). Applied systems:	Tool: PARAMASS (Tool of the developed integrated method) System: CATIA V5
Not functional requirements:	The designer have the right to open the cylinder head part in CATIA V5.
Explanatory notes	The time during the determination of the relationships between the the different kinds of parameters will be captured and measured.

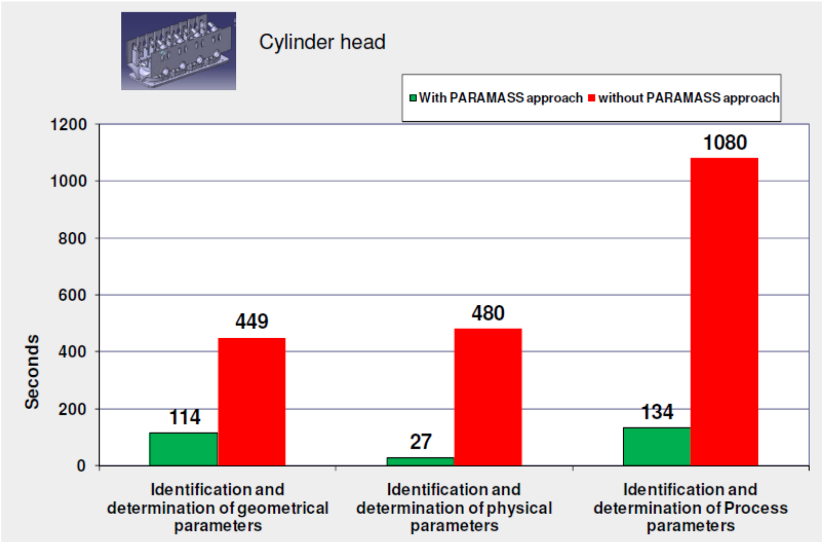


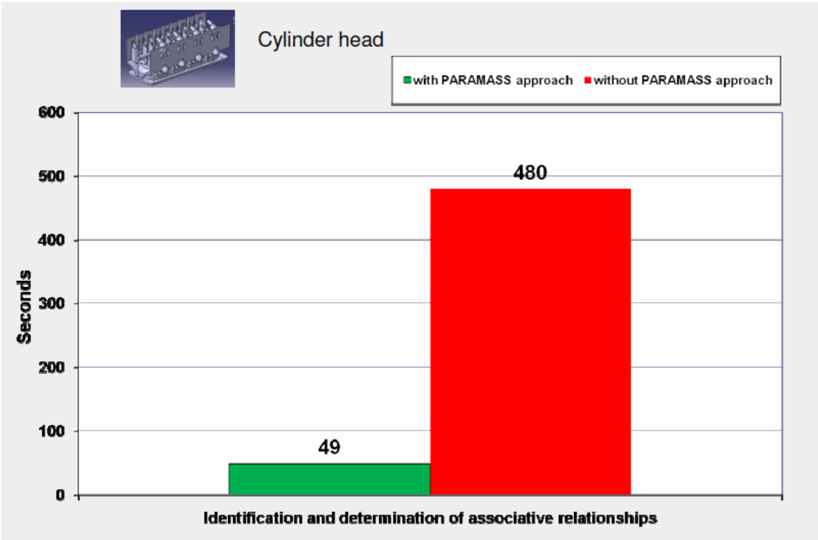
Use case measurement protocol
CYLINDER HEAD

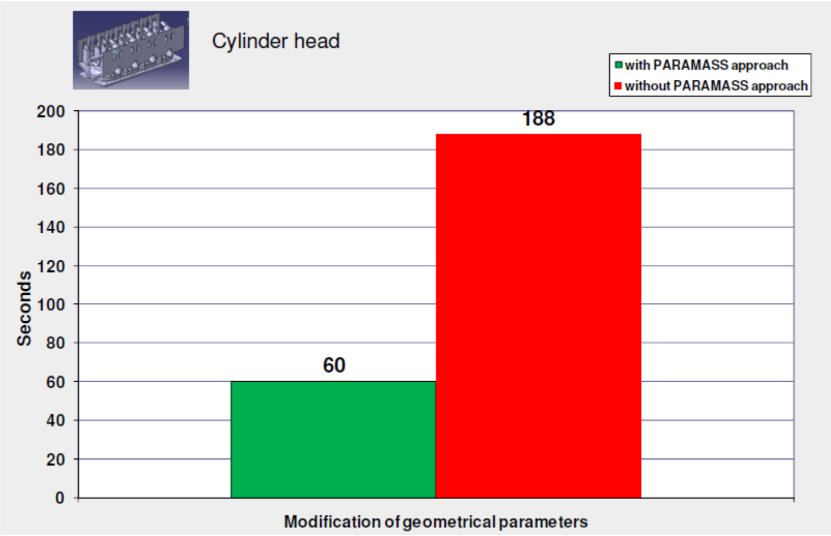
Use case name: Identification and determination of the cylinder head parameters and associative relationships				
Use case number: 4				
Level of the use case: Evaluation of phase I , II and III of the developed method				
Date: 01.05.2009				
Designer/Design group: with or without the method				
	With the PARAMASS approach		Without PARAMASS approach	
Phase 1: Identification and determination of parameters and associativity	Time (Minutes/ seconds)	Task fulfilled No○/Yes●	Time (Minutes/seconds)	Task fulfilled No○/Yes●
Geometrical parameters:				
The diameter of the cylinder bore:				
The diameter of the inlet valve:				
The centre of the inlet valve:				
The axis of the inlet valve:				
The inlet valve plane:				
The diameter of the exhaust valve:				
The centre of the exhaust valve:				
The axis of the exhaust valve:				
The exhaust valve plane:				
The centre of the spark plug:				
The diameter of the spark plug:				
The inlet spring plane:				
The exhaust spring plane:				
The inlet cam axis:				
The exhaust cam axis:				
The inlet first spine:				
The inlet second spine:				
The exhaust first spine:				
The exhaust second spine:				
The diameter of the cylinder head fixing points:				
The coordinates of the cylinder head fixing points:				
The axis of the cylinder head fixing points:				
The inlet valve axis:				
The exhaust valve axis:				
Sum of the measured				

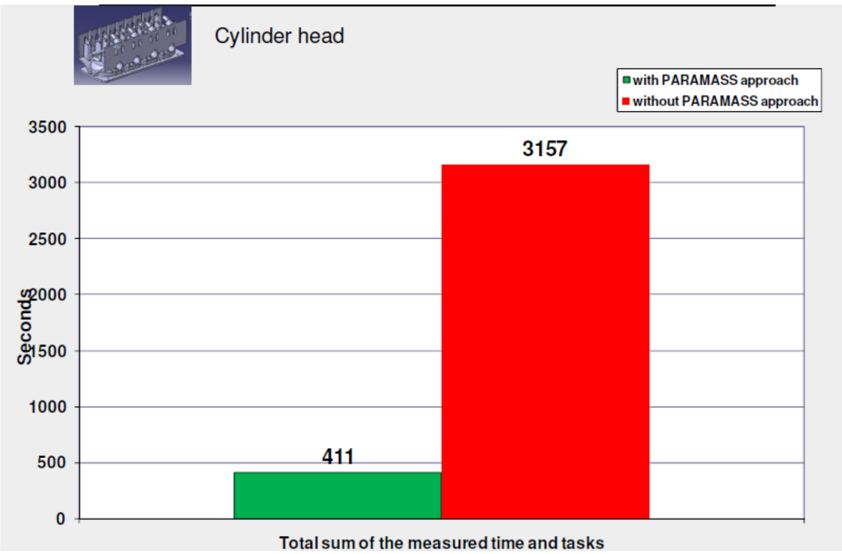
Results of the Use Cases for a cylinder head:

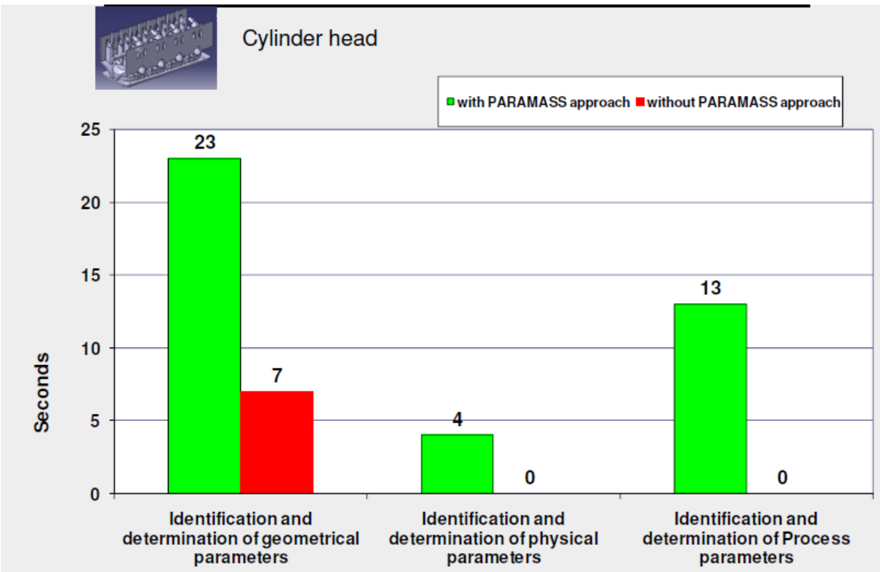

Design of the piston without PARAMASS
Design of the piston with PARAMASS
Minutes
100
90
80
70
60
50
40
30
20
10
0
62
86
43
61
Desing of the piston by CAD novice designer
Desing of the piston by CAD expert designer

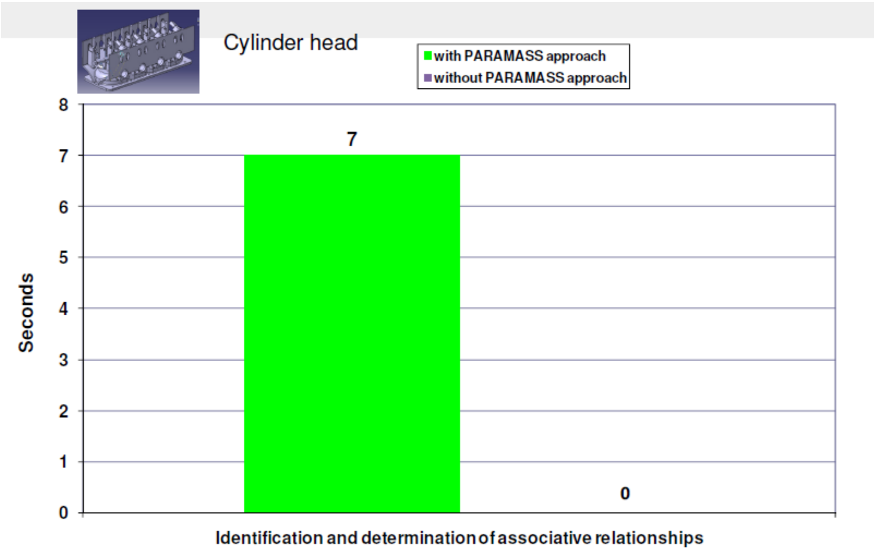

Cylinder head
With PARAMASS approach
without PARAMASS approach
Seconds
1200
1000
800
600
400
200
0
114
449
27
480
134
1080
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters

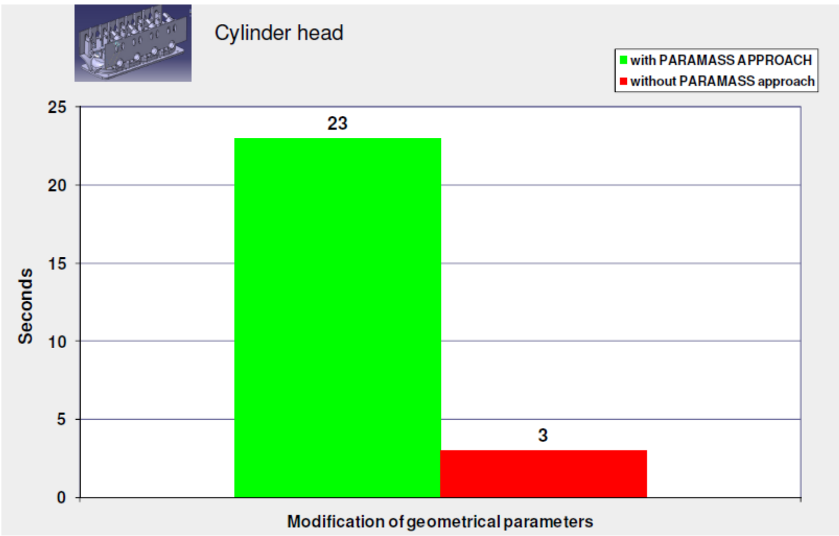

Cylinder head
with PARAMASS approach
without PARAMASS approach
Seconds
600
500
400
300
200
100
0
49
480
Identification and determination of associative relationships

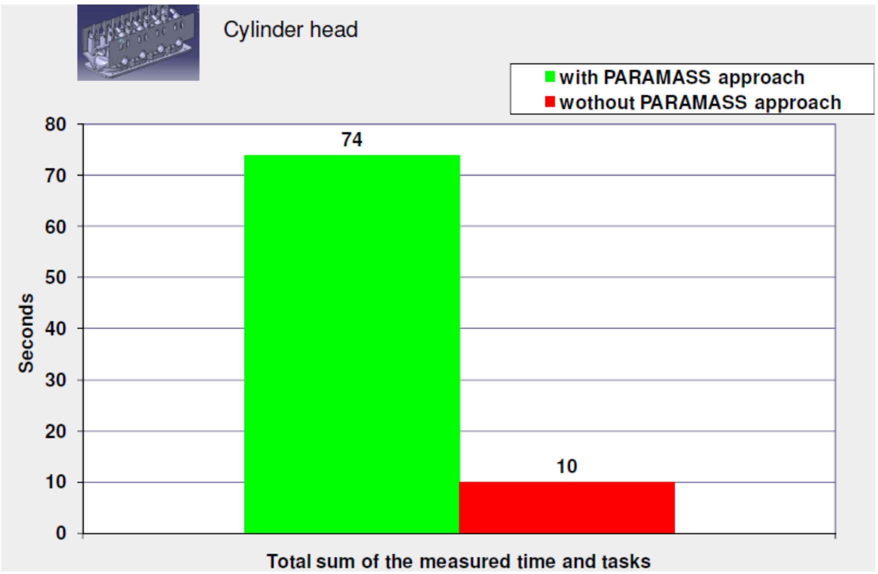

Cylinder head
with PARAMASS approach
without PARAMASS approach
Seconds
188
60
Modification of geometrical parameters


Cylinder head
with PARAMASS approach
without PARAMASS approach
Seconds
3157
411
Total sum of the measured time and tasks


Cylinder head
with PARAMASS approach
without PARAMASS approach
Seconds
23
7
4
0
13
0
Identification and determination of geometrical parameters
Identification and determination of physical parameters
Identification and determination of Process parameters


Cylinder head
with PARAMASS approach
without PARAMASS approach
Seconds
8
7
6
5
4
3
2
1
0
7
0
Identification and determination of associative relationships


Cylinder head
with PARAMASS APPROACH
without PARAMASS approach
Seconds
25
20
15
10
5
0
23
3
Modification of geometrical parameters


Cylinder head
with PARAMASS approach
wothout PARAMASS approach
Seconds
80
70
60
50
40
30
20
10
0
74
10
Total sum of the measured time and tasks

Appendix VI (Source code of the PARAMASS tool)

The PSM and ASM approach have been integrated in Excel “spread sheets” and the algorithm and VBA data base (source code) can be seen in this section of the work.

```
Option Explicit
Public StartZeit As Double
Public EndZeit As Double
Public GesamtAnzahlDeterminanten As Double
Public OrdnungGesamtMatrix As Integer
Private StartZeile As Integer
Private StartSpalte As Integer
Public Function Fakultaet(i As Integer) As Double

  Dim j As Integer
    Fakultaet = 1
    For j = 1 To i
      Fakultaet = Fakultaet * j

  Next

End Function
Private Sub Abhaengigkeiten()

  ' ************************************************************
  '     ABHAENGIGKEITEN (English: Relationships)
  ' ************************************************************

  ' Dimensionierung (English: dimensioning)
  Dim Spalte As Integer
  Dim zaehler As Integer
  Dim A As Matrix
  Dim ZwischenMatrix As Matrix
  Dim ZwischenCollection As Collection
```

```
Dim Zeile As Integer
Dim i As Integer
Dim j As Integer
Dim Value As Integer

StartZeile = 6
StartSpalte = 2
Cells(4, 4) = "Start"

'Application.Cursor = xlWait

' Anzahl der benutzten Zeilen (English: number of the cells)
Cells(4, 4) = "Matrixgröße bestimmen"
   OrdnungGesamtMatrix = StartZeile
   Do Until Cells(OrdnungGesamtMatrix, 1) = ""
      OrdnungGesamtMatrix = OrdnungGesamtMatrix + 1

Loop

OrdnungGesamtMatrix = OrdnungGesamtMatrix - StartZeile
   ' Matrix füllen (English: Filling the matrix)
Cells(4, 4) = "Matrix füllen"
   Set A = New Matrix
   For Zeile = 0 To OrdnungGesamtMatrix - 1
      For Spalte = 0 To OrdnungGesamtMatrix - 1

      If Cells(StartZeile + Zeile, StartSpalte + Spalte) = "x" Then

         Value = 1

      Else

         Value = 0
```

```
        End If

        A.AddValue Zeile + 1, Spalte + 1, Value

      Next

      A.UrSprungsZeilen.Add (Zeile + 1)

   Next
     ' Anzahl der Gesamtoperationen festlegen (English: Number of operations)
   GesamtAnzahlDeterminanten = Me.Fakultaet(A.Ordnung) * 1 / 2 * A.Ordnung + OrdnungGesamtMatrix
      zaehler = 0
      ' Matrix reduzieren um unabhängige Bauteile (English: Relationships)    Cells(4, 4) = "Matrix minimieren" (English: minimazation of the matrix)
      Set ZwischenMatrix = A.MinimierteMatrix
      Set A = ZwischenMatrix
      ' Abhängigkeit bestimmen (English: define the relationships)
   Cells(4, 4) = "Abhängigkeit bestimmen"
      If A.Ordnung > 1 Then
         Set ZwischenCollection = A.Abhaengig
         ' Auswertung der Ergebnisse (English: computation of the results)
      Cells(4, 4) = "Auswertung der Ergebnisse"
         Cells(3, 2) = ZwischenCollection.Count

      For i = 1 To ZwischenCollection.Count

         ' Buchstaben rot
         Cells(StartZeile + A.UrSprungsZeilen(ZwischenCollection(i)) - 1, 1).Font.Color = vbRed
         Cells(StartZeile - 1, StartSpalte + A.UrSprungsZeilen(ZwischenCollection(i)) - 1).Font.Color = vbRed

         ' Buchstaben fett
```

```
        Cells(StartZeile + A.UrSprungsZeilen(ZwischenCollection(i)) - 1, 1).Font.Bold =
True
        Cells(StartZeile - 1, StartSpalte + A.UrSprungsZeilen(ZwischenCollection(i)) -
1).Font.Bold = True

      Next
     Else
        Cells(3, 2) = 0
      End If
      zaehler = 0
   Application.Cursor = xlDefault

   Cells(4, 4) = " "

   Tabelle1.Activate

End Sub

Public Function Fortschritt() As Double

   Dim NochBenoetigteZeit As Double
   Static UpdateZeit As Double
   Static zaehler As Double
   Dim t As Double

   If StartZeit > UpdateZeit Then

      zaehler = 0

   End If

   zaehler = zaehler + 1

   Fortschritt = zaehler / GesamtAnzahlDeterminanten
```

```
    t = Time - UpdateZeit

    'Cells(4, 2) = Fortschritt

    If Time - UpdateZeit > 0.00001 Then

        ' Berechnen der voraussichtlich noch benötigten Zeit
        NochBenoetigteZeit = (Time - StartZeit) / Fortschritt

        'Cells(5, 2) = NochBenoetigteZeit

        UpdateZeit = Time

    End If

End Function

Private Sub CommandButton1_Click()

    Range(Cells(2, 2), Cells(4, 6)).Clear

    MatrixBefuellen

    Abhaengigkeiten

    Priorisieren

    AdapterModell

End Sub

Public Sub MatrixBefuellen()
```

```
'Dimensionierung
Dim Zeile1 As Integer
Dim i As Integer
Dim Zeile As Integer
Dim Spalte As Integer
Dim vorhanden As Boolean
Dim Dummy As Variant

' #######################
' Matrixbefüllung (English: filling the matrix)
' #######################

Range(Cells(5, 1), Cells(150, 150)).Clear

For i = 4 To Worksheets.Count

    Zeile1 = 8

    vorhanden = False

    Zeile = 6

    Do Until Cells(Zeile, 1) = ""

        If Worksheets(i).Cells(1, 2) = Cells(Zeile, 1) Then

            vorhanden = True

        End If

        Zeile = Zeile + 1

    Loop
```

```
If vorhanden = False Then
   Cells(Zeile, 1) = Worksheets(i).Cells(1, 2)

End If
Zeile1 = Zeile1 + 1
Do Until Worksheets(i).Cells(Zeile1, 1) = ""
   vorhanden = False
   Zeile = 6
   Do Until Cells(Zeile, 1) = ""
      If Worksheets(i).Cells(Zeile1, 1) = Cells(Zeile, 1) Then
         vorhanden = True
      End If
      Zeile = Zeile + 1
   Loop
   If vorhanden = False Then
      Cells(Zeile, 1) = Worksheets(i).Cells(Zeile1, 1)

   End If
```

```
        Zeile1 = Zeile1 + 1

    Loop

Next

Zeile = 6


Do Until Cells(Zeile, 1) = ""

    Cells(5, Zeile - 4) = Cells(Zeile, 1)

    Zeile = Zeile + 1

Loop

' Schleife über alle Tabellenblätter (English: Loop)
For i = 2 To Worksheets.Count

    Zeile1 = 8

    Do Until Worksheets(i).Cells(Zeile1, 1) = ""

        If Worksheets(i).Cells(Zeile1, 2) = "x" Then

            If Worksheets(i).Cells(Zeile1, 6) = "x" Then

                Zeile = 6

                Do Until Cells(Zeile, 1) = Worksheets(i).Cells(1, 2) Or Zeile > 32000

                    Zeile = Zeile + 1
```

```
    Loop

    Spalte = 2
    Do Until Cells(5, Spalte) = Worksheets(i).Cells(Zeile1, 1) Or Spalte > 255

        Spalte = Spalte + 1

    Loop

    Cells(Zeile, Spalte) = "x"

Else

    Zeile = 6

    Do Until Cells(Zeile, 1) = Worksheets(i).Cells(Zeile1, 1) Or Zeile > 32000

        Zeile = Zeile + 1

    Loop

    Spalte = 2
    Do Until Cells(5, Spalte) = Worksheets(i).Cells(1, 2) Or Spalte > 256

        Dummy = Worksheets(i).Cells(1, 2)
        Spalte = Spalte + 1

    Loop

    Cells(Zeile, Spalte) = "x"

End If
```

```
      End If

      Zeile1 = Zeile1 + 1

    Loop

  Next

  ' Formatieren der Spaltenüberschriften
  Rows("5:5").Select
  With Selection
    .HorizontalAlignment = xlGeneral
    .VerticalAlignment = xlBottom
    .WrapText = False
    .Orientation = 90
    .AddIndent = False
    .ShrinkToFit = False
    .MergeCells = False
  End With

  Columns("B:IY").Select
  Range(Selection, Selection.End(xlToRight)).Select
  Selection.ColumnWidth = 3

  Cells(6, 2).Activate
  Cells(6, 2).Select

End Sub

Private Sub CommandButton2_Click()

  Priorisieren

End Sub
```

```
Public Sub Priorisieren()

    Dim Zeile As Integer
    Dim Spalte As Integer
    Dim Bauteil As Bauteil
    Dim BauteileCollection As Collection
    Dim i As Integer
    Dim j As Integer

    Set BauteileCollection = New Collection

    If Cells(3, 2) > 0 Then

        MsgBox ("Es gibt eine oder mehrere Zirkelabhängigkeiten in der Matrix!")

        Exit Sub

    End If

    ' Bauteilcollection füllen (English: Part collection)
    Zeile = 6
    Do Until Cells(Zeile, 1) = ""

        Set Bauteil = New Bauteil
        Bauteil.Name = Cells(Zeile, 1)
        Bauteil.Ebene = 1
        BauteileCollection.Add Bauteil

        Zeile = Zeile + 1

    Loop

    ' Ebenen zuordnen
```

```
Spalte = 2
Zeile = 6

Do Until Cells(5, Spalte) = ""

   For i = 1 To BauteileCollection.Count

      If BauteileCollection(i).Name = Cells(5, Spalte) Then

         Set Bauteil = BauteileCollection(i)

      End If

   Next

   Zeile = 6
   Do Until Cells(Zeile, 1) = ""

      If Cells(Zeile, Spalte) = "x" Then

         For i = 1 To BauteileCollection.Count

            If BauteileCollection(i).Name = Cells(Zeile, 1) Then

               If BauteileCollection(i).Ebene < Bauteil.Ebene Then

               Else

                  Bauteil.Ebene = BauteileCollection(i).Ebene + 1

               End If

            End If
```

```
            Next

        End If

        Zeile = Zeile + 1

    Loop

    Spalte = Spalte + 1

Loop

Tabelle2.Range(Tabelle2.Cells(5, 2), Tabelle2.Cells(100, 100)).Clear
Zeile = 5

For i = 1 To BauteileCollection.Count

    Spalte = 2
    Tabelle2.Cells(Zeile, 1) = "Ebene " + Str(i) + ":"
    For j = 1 To BauteileCollection.Count

        If BauteileCollection(j).Ebene = i Then

            Tabelle2.Cells(Zeile, Spalte) = BauteileCollection(j).Name

            Spalte = Spalte + 1

        End If

    Next

    Zeile = Zeile + 1

Next
```

```
End Sub

Public Sub AdapterModell()

    'Dimensionierung
    Dim Zeile1 As Integer
    Dim i As Integer
    Dim Zeile As Integer
    Dim Spalte As Integer
    Dim vorhanden As Boolean
    Dim Dummy As Variant

    ' ###########################
    ' Adaptermodelle analysieren (English: analysing adapter models)
    ' ###########################

    Tabelle3.Range(Tabelle3.Cells(5, 1), Tabelle3.Cells(500, 3)).Clear
    For i = 4 To Worksheets.Count

        Zeile1 = 8

        Do Until Worksheets(i).Cells(Zeile1, 1) = ""

            For Spalte = 2 To 5

                If Worksheets(i).Cells(Zeile1, Spalte) = "x" Then

                    Zeile = 5

                    Do Until Tabelle3.Cells(Zeile, Spalte - 1) = ""

                        Zeile = Zeile + 1
```

```
            Loop

            Tabelle3.Cells(Zeile, Spalte - 1) = Worksheets(i).Cells(Zeile1, 1) + " - " +
Worksheets(i).Cells(1, 2)

          End If

        Next

        Zeile1 = Zeile1 + 1

      Loop

    Next

End Sub
```